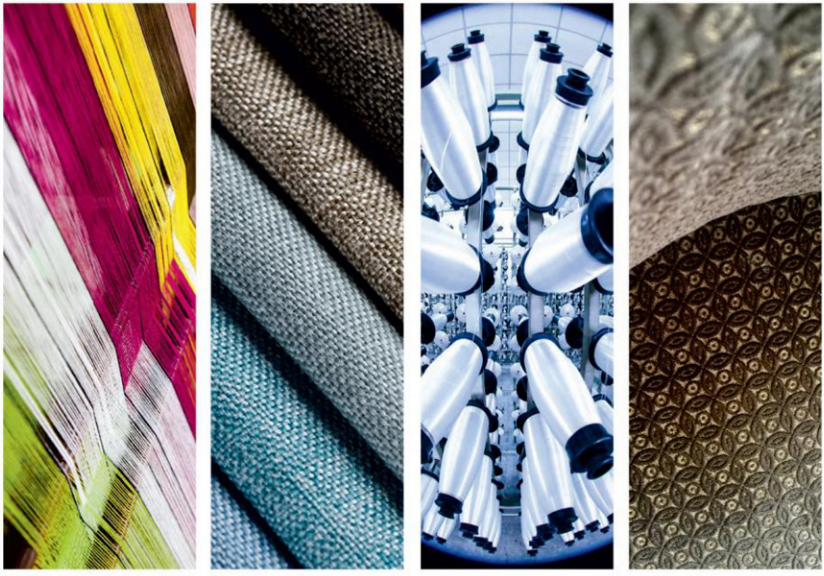
Engineering Textiles

Integrating the Design and Manufacture of Textile Products

Second Edition



Yehia E. Elmogahzy

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Engineering Textiles

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Preface

Over the years, the textile industry has been perceived as a "technology-based" industry using manufacturing technologies that have evolved over the years in terms of power, speed, automation, and process control, but they have remained the same in principle. This is a total misperception that has been created by the fact that it is one of the oldest industries in the world and it has been primarily based on using commodity materials. This misperception was also solidified by the significant redistribution of the industry, which began in the last decade of the 20th century and the migration of the industry to cheap-labor regions around the world. These dramatic changes can partly be blamed on the traditional textile industry that has largely failed to represent itself as a value-added industry and preferred to remain as a mass production-discount industry focusing on lowering cost and handling quality issues through business deals rather than innovations and design concepts. Now, these approaches are being put to rest in many sectors of the industry, and many companies in industrial countries are redirecting their efforts to product development and new innovations.

In parallel with textile technology, textile science and textile engineering have been progressing almost as if they had been in a different planet with limited connection with the industry. Textile scientists developed models to explore and predict the complex nature of fibrous assemblies and to bring about fiber contributions that can enhance the performance characteristics of textiles beyond the traditional thresholds. Yet, many sectors of the industry remained largely unresponsive to these developments. According to the late John Hearle "while other industries marched into the second half of the 20th century utilizing more quantitative design approaches inspired by the growth of the science of applied mechanics and the theory of elasticity, these approaches were not transformed to the textile industry, which continued to implement empiricism and augmented the qualitative insights in its product design applications, with the one exception being the mechanical and power-driven design of textile machinery." Well, following this assessment, what appears to be the main cause of not transforming science into the industrial implementation phase is the lack of textile engineering since quantitative design approaches are not merely to be inspired or admired, but rather to be transformed into prototypes and design models that can be transformed to produce innovative products. This missing link was the main reason for writing this book.

The term "textile engineering" has been known to the scientific community around the world since the early 20th century. However, implementation of engineering concepts in the textile field can be traced back to the ancient Egyptian who produced linen fibers to weave fabrics that could be used for clothing and wrappings of mummies that

lasted over 5000 years. The technologies used to produce these fibers and their assemblies could not have been possible without design conceptualization and reliable design analysis, which represent the essence of today's engineering. Textile engineering cannot be treated as a derivative of other engineering disciplines as in the case of material engineering, which is a derivative of mechanical engineering, or biochemical engineering, which is a derivative of chemical engineering. It is an interdisciplinary field in which scientific principles, mathematical tools, and techniques of engineering, physics, and chemistry are all utilized in a variety of creative applications including the development of new fibers, the innovation of fibrous elements that can be combined with other nonfibrous materials, and the design of fiber-to-fabric systems that aim at optimizing machine-fiber interaction and producing value-added fibrous products. A logical derivative of textile engineering is fabric engineering that is prompted by the growing field of technical textiles including smart textiles, medical textiles, and transport textiles.

The primary theme of this book is "engineering textiles." Although this book represents a second edition of the book carrying the same title, it is substantially different from the first edition in many aspects including the following:

- New chapter titled "textile engineering as a scientific discipline." This chapter was prompted by the confusion and the lack of recognition of textile engineering as an independent discipline and the critical role of this category of engineering in interdisciplinary design projects. It also covers many recommendations to textile institutions that are having or developing textile engineering programs.
- New chapter on design for sustainability in the textile and fashion industry. This chapter provides a detailed review of key sustainability concepts and how they can be implemented in the textile and fashion industry.
- New chapter on E-textiles including some of the new developments in this field that were made in recent years.

The remaining chapters were also substantially modified to reorganize thoughts on product development and design conceptualization. Examples of new topics added in this edition include the following:

(a) A special attention to the fashion industry as a solid partner to the textile industry including key differences between fashion design and engineering design concepts
(b) The different phases of market evolution in the textile and fashion industry—(i) the customization era, (ii) the production-focus era, (iii) the product-focus era, (iv) the consumer-focus era-phase I (sales), (v) the consumer-focus era-phase II (marketing), and (vi) the information-focus (societal marketing) era (Chapter 2)
(c) Differences between product development in small and large businesses (Chapter 3)
(d) The concept of "Engineering Operating System, EOS," or the bridging between textile science, textile engineering, and textile technology (Chapter 4)
(e) The "Concept Modeling Optimization Manufacturability" system, or CMOM, which provides guidelines to textile and fashion engineers in implementing systematic steps of product design (Chapter 5)
(f) Design thinking and lean startup design (Chapter 6)

The intended reader of this book covers a wide range of qualification including the following:

(1) Undergraduate and graduate students in textile and fashion institutions who are studying product development, textile science, and textile engineering
(2) Textile engineers working in multidisciplinary design projects of traditional and technical textiles
(3) Textile technologists working in supervisory positions or as members in product development teams
(4) Nontextile engineers who are involved in design projects containing fibrous materials and fibrous assemblies
(5) Product developers of textile and fashion products
(6) Textile and fashion scientists who are seeking new research ideas
(7) College professors who are involved in STEM programs and interdisciplinary research activities

It is my sincere hope that this new edition will represent a contribution to the textile and fashion industry both in grasping key fundamental aspects and in implementing reliable design tasks.

Yehia E. Elmogahzy

Acknowledgment

I would like to acknowledge my wife Mona Saraya for standing by my side not only in completing this book but also throughout the many consulting work that I do in the United States and abroad in which I have to stay away from home for weeks and months.

Textile engineering as a scientific discipline

1

1.1 Introduction

Since this book is entirely about engineering textiles, it will be useful to begin its contents by introducing the meaning of textile engineering, particularly to engineers who belong to different engineering societies. First, it should be noted that the term "textiles" begins with the four-letter word "text," which has a well-established meaning in the publishing field. The connection between "textiles" and "text" stems from the basic product structure; to make textiles, you need fabric, and to produce a text, you need paper [1,2]. Both fabric and paper are produced using a form of binding or weaving mechanism, and the word "weave" in Latin is the verb "texerel."

The term "textile engineering" has been around in the scientific community around the world since the early 20th century. However, its full meaning has not been well recognized by both the industrial and the academic environments in comparison with other engineering professions such as mechanical, electrical, or civil engineering. Indeed, there is only a handful of academic institutes that encompass textile engineering programs, and most people working in engineering professions around the world may have narrow views of what textile engineering is all about. This lack of recognition is a result of many reasons including a lack of clear identity of many academic programs of textile engineering in comparison with other engineering programs and a great deal of overlapping between tasks performed by textile engineers and other types of engineers in the industrial environment.

The original intention to establish an independent discipline of textile engineering stemmed from market needs of this type of engineering and the high degree of specificity of this critical profession. As a result, textile engineering could not be treated as a derivative of other engineering disciplines, as in the case of material engineering, which is a derivative of mechanical engineering, or biochemical engineering, which is a derivative of chemical engineering. It also could not be treated as an interdisciplinary branch of engineering such as industrial engineering or biomedical engineering. In addition, the textile industry being massive-labor industry serving billions of people around the world and creating trillions of dollars in revenues has made it necessary to establish an independent category of engineering that primarily serves the industry in providing an immense service to humanity and civilizations. Furthermore, the textile industry, being the oldest industry in the world, has acquired special attributes and criteria that are not duplicated in any other industry. Even today, many engineering approaches and terminologies used in the textile industry are not known in other industries. The following unique criteria represent only a few of numerous examples that can justify the need for independent textile engineering programs [3–6].

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Diverse sources of raw materials. The building block of all textiles is fiber, and the source of fiber may be classified by its chemical origin, internal structure, molecular weight, and the degree of crystallization. Fibers may be classified into two main categories: natural fibers and manufactured fibers. Natural fibers are divided into plant, animal, or mineral. Most plant fibers are cellulose based (e.g., cotton, jute, and ramie) separated from the plant stalk, stem, leaf, or seed. Cellulosic fibers may be extracted from various plants growing naturally such as cotton fibers or from regenerated cellulose using chemical derivatization processes and wet spinning such as the case of viscose or modal fibers or by direct dissolution spinning process from organic solvents such as lyocell fibers. Animal fibers are protein based (wool, camel, mohair, silk, etc.) harvested from an animal or removed from a cocoon or web. Mineral fibers (e.g., asbestos fibers) are those that are mined from the earth. Except for silk, natural cellulose- and protein-based fibers are obtained in short lengths and are called staple fibers, while silk is considered as a continuous filament fiber. Manufactured or man-made fibers (e.g., nylon, polyester, and rayon) are produced by a wide variety of chemical processes. These fibers are generally semicrystalline polymers that are spun into filaments, uniaxially oriented during the melt, dry, or wet spinning process, and then spun into continuous filaments that can be cut into staple fibers.

Flexible structures. The textile industry must maintain a flexible material stream throughout the entire flowchart of processing. Fibers being the building blocks of all textile products are typically made from long-chain molecules; they have a high aspect ratio (length/diameter ratio); they have low tensile modulus and low flexural rigidity; they must exhibit smooth surface characteristics that allow them to slide against each other and against other solids to be converted from one form of flexible structure to another; they must yield flexible products that are easily manipulated in different applications. These aspects make fibers and textiles a unique category of material that requires special handling in processing and designing of products.

Intimacy with human body. Many textile products come in intimate contact with human body, acting as intermediate portable systems between the human skin and the surrounding environment. This requires special design approaches to allow a combination of protection and comfort. The protection aspect may range from providing warm or cool feeling under different weathering conditions to harsher applications such as gasproof, waterproof, dustproof, fire-resistant, flame-resistant, and bulletproof applications in which deflection, rebounding, absorption, and impact resistance represent key design criteria. A key design challenge here is the ability to perform these protection characteristics while maintaining light weight, small thickness, and flexibility. Meanwhile, textiles must provide both tactile comfort and thermophysiological comfort. Optimum trade-off between comfort and protection has been a specialty of textile engineering for many years.

Unique binding mechanisms. Textiles are formed using creative binding mechanisms. Fibers are not glued or cemented; they are twisted or wrapped to form flexible yarns. Fabrics are made by interlacing or interlooping of yarns to provide strong structures yet maintain flexibility. Even when dyeing and finishing are applied to fabrics, they must maintain the original flexibility and provide surface smoothness. A yarn or

fabric structure represents a complex structural model, which is largely anisotropic and viscoelastic in nature, and this requires a great deal of knowledge in the mechanics of flexible structures and thermodynamics of polymeric materials that represent essential aspects of textile engineering curricula.

Blending fibers of different degrees of variability. As indicated earlier, fibers being the primary material in engineering textiles can be of natural sources (vegetable or animal) or of man-made sources (organic or inorganic). This diversity not only provides unlimited resources of raw materials and unlimited options of functional characteristics but also introduces many processing and chemical challenges, particularly in the mixing and blending processes of different fibers. For example, the fact that fibers can be hydrophobic or hydrophilic imposes special methodologies in dry processing (spinning and weaving) and chemical processing (dyeing and finishing). Characteristics of blended fibers are hardly linearly additive, and they may deviate significantly from the theoretical average. This requires special blending techniques to compensate for these deviations.

The sustainability challenge. Most fibers produced today utilize a great deal of natural nonrenewable resources, petroleum based or agricultural based. They require a great deal of energy and water consumption. The entire fiber-to-fabric process is associated with significant gas emission, toxic chemicals, air pollution, and all kinds of waste. These challenges cannot be overcome without a significant involvement of textile engineers.

The complexity associated with material transformation. Fibrous structures are quite complex as they may consist of billions of fibers that must be reduced to few hundreds of fibers in subsequent processes. This requires sequential conversions from three-dimensional structures (fiber bale), to two-dimensional structures (fiber mats), to linear structures (fiber strands), then back to two-dimensional or three-dimensional structures (fabrics and composites). These structural transitions must be achieved at a minimum loss of flexibility and at a high level of dimensional stability. These criteria do not represent typical challenges in many other engineering professions.

The need for convenient dimensions. In the mist of achieving the complex tasks mentioned earlier, many traditional engineering terms cannot be used with any extent of reliability or convenience in textile engineering. As a result, a diameter or thickness of a linear structure such as a fiber or a yarn must be expressed, not in the traditional length units such as inch or meter but in a nontraditional term such as mass per unit length (tex or denier), and the weight of three-dimensional fibrous structure such as woven or knitted fabric must be expressed in mass per unit area. Furthermore, textile engineers do not define mechanical properties such as stress and work in the traditional sense; instead, they use uniquely different terminologies such as specific stress in gram-force per tex, where tex is a weight per unit length or a weight per unit area depending on the fibrous structure being evaluated.

The stochastic design of textile machinery. The design of a textile machinery represents an ultimate complexity to any mechanical engineer, and without a textile engineer on board, it will be impossible to even conceive the design conceptualization of this type of machinery. The fact that fibers are discrete and they exhibit very high

variability requires special machine designs that can accommodate the massive number of input fibers and the very high variability in all fiber characteristics. Joint efforts between textile and mechanical engineers have resulted in developing smart machines before this term was ever coined. In the early process of handling fibers, textile machines must be designed in such a way that not only manipulate and convert the raw material into an intermediate or final product but also, and often more importantly, accommodate the stochastic and discrete nature of raw material and the associated complex machine-material interaction. This concept does not exist to the same extent in other engineering professions. As a result, progressive fiber handling and autoleveling have been part of the textile industry for many years. Arguably, the concept of self-adjusted machinery was first introduced by textile engineers. This is where machine can respond to incoming material variations in thickness or density by dynamically even out these variations so that a consistent output material can be produced.

The interaction between fibers and other materials. In today's wide range of high-performance products, fibers can be mixed with soils of different pore sizes for various geotextile applications, fibers must interact with internal human organs in many implant medical applications, fibers can be mixed with metallic or solid polymeric structures in many composite applications, and fibers can play vital roles as conductive or sensory items in many electrical engineering applications. Without understanding fibrous structures, flexibility and conformity aspects, and surface characteristics, these applications would never have come to light.

The lack of recognition of textile engineering as one of the most critical engineering professions represents a dual responsibility of the textile industry and the academic institutes. In the industrial environment, most industrial segments of the textile industry from fibers to end products are primarily manufacturing driven. Indeed, divisions such as product development, product design, or research and development (R&D) departments are hardly found in the traditional textile industry. As a result, the common perception about the industry has been reduced to an industry, which is largely systematic, primarily low tech, and significantly operational.

In one of the author's exchanges with some representatives of the Accreditation Board for Engineering and Technology (ABET), it was clear that their view about textile engineering was that it is more of an engineering technology than engineering. On the other hand, most textile academic institutes follow the industry instead of leading it. This has been evident by the types of senior graduation projects that textile students undertake and even by the type of research that most textile scientists do. It is my hope that this book will alert both the industry and the academic institutes to this critical issue and lead to a better realization of textile engineering as a stand-alone engineering discipline, which, if developed properly, can effectively and efficiently serve all human being. Obviously, the field of textile engineering is open to all contributions from other engineering categories, and a textile engineer should share and cooperate with other engineers in all aspects associated with the make of a textile product. Indeed, an integrated textile project running without a textile engineer would be like a ship sailing without a shipmaster.

1.2 The status of textile engineering education program: Engineering versus engineering technology

According to the Accreditation Board for Engineering and Technology [7] (ABET), engineering and engineering technology are two separate categories of engineering but closely related professional areas that differ in two key aspects: curricular focus and career paths. Engineering programs often focus on theory and conceptual design, while engineering technology programs usually focus on application and implementation. Engineering programs typically require additional, higher-level mathematics, including multiple semesters of calculus and calculus-based theoretical science courses, while engineering technology programs typically focus on algebra, trigonometry, applied calculus, and other courses that are more applied than theoretical. Graduates from engineering programs are called engineers, and they often pursue entry-level work involving conceptual design or research and development. Graduates of 4-year engineering technology programs are called technologists, while graduates of 2-year engineering technology programs are called technicians. Implementation of these education models may vary from one engineering program to another provided that the core engineering courses are fulfilled. Traditionally, the primary emphasis of engineering accreditation has been on the design aspects of engineering. However, the meaning of engineering design has undergone substantial changes in recent years. The era of "design strictly for functional performance" has long gone. Today's products and processes must account for many new aspects including [3,4] global social awareness, humanities, sustainability aspects, global communication, and developmental speed. A product that is designed or developed without these aspects in mind is likely to encounter a short life cycle and limited use. As a result, the accreditation criteria for engineering and engineering technology programs should be continuously modified and appropriately upgraded to accommodate the rapid changes in consumer's behavior given the fact that some products can become obsolete at the early stage of their service life. This means that the addition of critical courses relevant to consumer's behavior, globalization, and world's economics will be important. Furthermore, statistics and probability courses should not be incorporated in engineering programs in their generic forms. Instead, they should be fully integrated into engineering and technology courses to provide students with understanding of the differences between deterministic design and probabilistic design [3,4]. In deterministic design, engineers rely mainly on safety factors to assure product survivability and minimum failure rate. In probabilistic design, potential failures are predictable, and weak-link effects are preidentified.

The ABET models provide flexibility to different schools of textiles to develop derivative programs of textile engineering and textile technology. For example, the college of textiles at North Carolina State University, United States, which is undoubtedly the world's top school of textiles, has three programs of textile engineering [8]: (1) textile engineering, chemical processing; (2) textile engineering, information systems; and (3) textile engineering, product engineering. These programs use the core courses of most engineering programs including three courses in calculus, one course

in applied differential equations, two courses of physics, and one or more courses in statics or dynamics. The difference between the three programs is primarily in engineering specialty courses. In the chemical processing program, two chemistry courses are used, one on molecular science and the other on quantitative chemistry. In addition, three chemical engineering courses are offered covering chemical processes and transportation. Textile engineering aspects in this program are represented by 11 specialty courses covering many key subjects including polymer science and engineering, textile engineering science, engineered textile structures, thermodynamics for textile engineering, process system analysis and control, dyeing and finishing, and textile manufacturing processing. The information system program offers similar core engineering courses, but it is less on chemistry as it offers only one chemistry course and no chemical engineering courses. Similar textile engineering courses are offered in this program in addition to a course on information systems design. The product engineering program follows similar curriculum to the information system program with more emphasis on materials science courses such as the structures and properties of engineering materials and solid mechanics. The three textile engineering programs offer courses on statistics and probability and another course on six-sigma quality. Obviously, all textile engineering programs offer education of design skills through the contents of different courses and student's projects. The college of textiles at North Carolina State University also offers a textile technology program in which students must take two calculus courses, two physics courses, and two chemistry courses. In addition, many courses are offered on textile technology, statistics and probability, and quality control. The program also offers courses on economics, academic writing, humanities, and social science.

1.3 The extent of coordination between textile education and textile careers

In today's information era, developing a good education program may not be enough to graduate students that are ready to face the challenges of today's global industry. An education program must exhibit a good understanding of the current industry's status and a great vision of the future of the industry. Most textile programs around the world have followed the evolutionary changes in the industry over the years, but they have not played a significant role in leading the industry through education or scientific research even when they had the financial resources and the generous research funding that could have allowed them to play this role. As a result, the viability of many textile programs around the world has been under significant pressure in recent years, and many textile education programs have either completely collapsed or joined other programs only for the sake of survival.

On the education side, today's graduates of textile programs are struggling finding their career paths in the traditional textile industry. Indeed, it is often difficult to separate career paths of textile engineers from textile technologists, and the two jobs are hardly distinguishable in textile companies. This is largely due to the management structure of the textile industry, which has not changed over the last 50 years.

The traditional textile industry has been historically a production-focus industry with technology representing the driving force of virtually all the tasks in the industry. Many of the textile products produced today in the traditional textile industry largely follow the classic structures that were developed many years ago, and alteration of these structures has mainly been a result of new machine designs introduced to the industry over the years. Furthermore, intermediate products leading to the end product are typically produced by independent operations with minimum coordination between the different segments in the textile supply chain. Each segment typically focuses on the intermediate product it produces (i.e., fiber, yarn, or fabric) with minimum coordination with the subsequent operation in the supply chain. This traditional approach is called "product-in" approach [4] in which each segment focuses entirely on the product it makes regardless the effects of its product on the upcoming process or the end product. In a production-focus and technology-driven industry, there is normally little room for product development and innovative designs. As a result, textile engineers who are trained by education to perform rigorous engineering design and find optimum solutions to many problems are typically more involved in normal daily operations and largely single-task activities.

The aforementioned problems will ultimately be resolved by the increasing trend toward technical textiles and smart clothing [9,10]. These applications will provide immense opportunities for textile engineers to join engineers of other disciplines in the development of many innovative products. As indicated earlier, the use of fibrous materials requires a great deal of knowledge in textile basics. Textile engineers working in nontraditional products will certainly have this background in addition to their intense engineering education as described in the North Carolina State University education model. The role of textile education programs should then be on coordinating appropriate career paths for textile engineering graduates with the industry.

On the research side, it was indicated earlier that textile education programs have not played a significant role in leading the industry in research and development activities. This was not due to a lack of research funding. During the 1990s, the US Department of Commerce sponsored the so-called National Textile Center that consisted of all major schools of textile in the United States with over $150 million for the sake of promoting the US textile industry and creating a transition from traditional practices to more innovative approaches. Unfortunately, most of this funding was spent on administrative work, and little research coordination was made between scientists in the major universities. The 1990s also witnessed a significant decline in the US textile industry and a substantial migration of the industry to Asia.

In 2016, a new MIT institute to accelerate innovations in fibers and fabrics was announced by the secretary of the US Defense Department with a $317 million budget [11,12]. This institute represents a national public-private consortium led by MIT, consisting of manufacturers, universities, agencies, and companies. The proposed partnership included 32 universities, 16 industry members, 72 manufacturing entities, and 26 startup incubators, spread across 27 states and Puerto Rico. At this state of progress, it seems that this partnership is moving in the right direction. In 2017, a new center for the development and commercialization of advanced fabrics was officially opened with its headquarters in Cambridge, Massachusetts. This center aims

at developing and introducing US-made high-tech fabrics that provide services such as health monitoring, communications, and dynamic design. In 2018, smart clothing represented by a form of wearable soft hardware was developed at MIT under the sponsorship of this partnership. In this structure, researchers at MIT embedded high-speed optoelectronic semiconductor devices, including light-emitting diodes (LEDs) and diode photodetectors, within fibers that were then woven at Inman Mills, in South Carolina, into soft, washable fabrics and made into communication systems. This marks the achievement of a long-sought goal of creating "smart" fabrics by incorporating semiconductor devices.

1.4 The textile engineering position in the engineering world

Today, engineering disciplines such as civil, mechanical, electrical, and chemical engineering are considered as basic engineering disciplines. In addition, the 20th century witnessed the emergence of new engineering programs many of which were derivatives of the basic engineering disciplines. These can be described collectively as service and support branches of engineering in specialized areas, and they represent a logical evolution of the engineering field as engineers began to touch upon every aspect of life and reach out to different areas and various applications. Examples of these derivative engineering disciplines and their functions are listed in Table 1.1.

By the standard definition of derivative engineering, textile engineering cannot be considered as a derivative engineering discipline since it does not belong to a single parent basic engineering discipline. Instead, it represents a unique interdisciplinary field of engineering that combines approaches from mechanical engineering, electrical engineering, and chemical engineering in an integrated and seamless chain of processes in which numerous technological and management approaches are implemented to design, create, and produce a wide range of fibrous products. In addition, well-established fields such as fiber engineering and fabric engineering should be considered as derivative disciplines of textile engineering. The term "fiber engineering" has often been used by synthetic fiber producers to describe the process of polymer manipulation to produce fibers of different and diversified performance characteristics, and the term "fabric engineering" has been increasingly used in recent years to refer to the use of fabrics as membranes in technical applications such as architects and composite structures.

Another way to define textile engineering is as *an interdisciplinary field in which scientific principles, mathematical tools, and techniques of engineering, physics, and chemistry are all utilized in a variety of creative applications including the development of new fibers, the innovation of fibrous elements that can be combined with other nonfibrous materials, and the design of fiber-to-fabric systems that aim at optimizing machine-fiber interaction and producing value-added fibrous products*.

The earlier attempts to define textile engineering stem from the common practical elements involved in engineering textiles today. The argument about the uniqueness of this type of engineering is often derived from the fact that the basic ways of thinking

Table 1.1 Examples of derivative engineering disciplines and their functions [13–18].

Engineering discipline	Definition or function
Architectural engineering	A discipline associated largely with civil engineering. It deals with the technological aspects of buildings, including foundation design, structural analysis, construction management, and building operations
Highway engineering	A derivative of civil engineering that includes planning; design; construction; operation; and maintenance of roads, bridges, and related infrastructure to ensure effective movement of people and goods
Environmental engineering	A derivative of civil engineering or chemical engineering concerned with the development of processes and infrastructure for the supply of water, the disposal of waste, and the control of pollution of all kinds. It is a field of broad scope that draws on such disciplines as chemistry, ecology, geology, hydraulics, hydrology, microbiology, economics, and mathematics
Marine engineering	A derivative of mechanical engineering concerned with the machinery and systems of ships and other marine vehicles and structures
Industrial engineering	An interdisciplinary branch of engineering dealing with the design, development, and implementation of integrated systems of humans, machines, and information resources to provide products and services
Material engineering	A derivative of mechanical engineering that focuses entirely on material characterization, selection, and improvement
Petroleum engineering	A derivative of chemical engineering comprising the technologies used for the exploitation of crude oil and natural gas reservoirs
Biochemical engineering	A derivative of chemical engineering focusing on the application of engineering principles to conceive, design, develop, operate, or utilize processes and products based on biological and biochemical phenomena. It impacts a broad range of industries, including health care, agriculture, food, enzymes, chemicals, waste treatment, and energy

for textile engineering are supplied from different kinds of fundamental sciences and engineering disciplines including polymer chemistry, polymer physics, biometrics, biomechanics, physiology, psychology, ergonomics, human engineering, mechanical engineering, and chemical engineering. This makes it rather difficult to establish a scientific system associated with textile engineering based on a certain common scientific way and leads to the impression that textile engineering is a disordered assembly of scientific knowledge relating to textiles [19]. The validity of this argument is highly doubtful since it can hold for any engineering discipline and not only for textile engineering, particularly in view of the current trends of interdisciplinary efforts in all engineering fields. Indeed, all engineering disciplines including the old

ones need to be redefined in accordance to their current practices as the old definitions of say mechanical engineering based on Newton principles and electrical engineering based on Maxwell electromagnetic principles are things in the past. Any engineering discipline today has become a very complex network of interdisciplinary tasks to the point that we expect all engineering disciplines will ultimately be reduced to one term by the middle of this century, which is "integrated engineering."

Textile engineering is not the only interdisciplinary field of engineering. Table 1.2 lists other more recent engineering fields that follow the same model. Yet, textile engineering is often ill defined or overlooked in engineering lists. It is the author's opinion that the earlier definition of textile engineering should replace the current ambiguous

Table 1.2 Interdisciplinary fields of engineering [13–17].

Engineering discipline	Definition or function
Agricultural engineering	An interdisciplinary field initiated in accommodation to the expansion of the use of mechanized power and machinery on the farm. It utilizes appropriate areas of mechanical, electrical, environmental, and civil engineering; construction technology; hydraulics; and soil mechanics
Biomedical engineering	An interdisciplinary field in which the principles, laws, and techniques of engineering, physics, chemistry, and other physical sciences are applied to facilitate progress in medicine, biology, and other life sciences. It encompasses both engineering science and applied engineering to define and solve problems in medical research and clinical medicine for the improvement of health care
Computer-aided and software engineering	Computer-aided engineering: a discipline of engineering focusing on using computer software to solve engineering problems Software engineering: a discipline of engineering focusing on the process of manufacturing software systems (i.e., executable computer code and the supporting documents needed to manufacture, use, and maintain the code)
Nuclear engineering	A branch of engineering dealing with the production and use of nuclear energy and nuclear radiation
Forensic engineering	A relatively more recent discipline of engineering that has gained more popularity after recent terrorist attacks. It is applied toward the purposes of law through using various engineering techniques to solve problems associated with criminal or terrorism situations
Genetic engineering	A specialized engineering branch that uses the techniques of molecular cloning and transformation in many areas including improving crop technology and manufacturing of synthetic and human insulin through the use of modified bacteria

definitions of the textile engineering discipline in the literature in which textile engineering is describe by course offerings and not by substance and applications.

1.5 Closing remarks

An efficient and profitable transition from a total reliance on mass production to more customization (performance differential) approaches in the textile industry will require total coordination between textile science, textile technology, and textile engineering. Such coordination will necessitate greater attention to product diversity and applications, which means more emphasis on research and development in the textile industry without ignoring the aspect of textile experience and creative tasks. Obviously, subjective approaches will remain a part of this industry, but a greater effort should be made to convert many subjective approaches into more objective methodologies. This is particularly true for key consumer descriptive characteristics such as aesthetics and comfort, protection, performance, and easy-care properties. This subject will be discussed in more detail throughout this book.

The true challenge facing textile education has not been in the ability to develop unique engineering or technology programs that fit the industry's needs of qualified personnel or in conducting top-quality research that can serve the industry in all sorts of innovations and developments. The true challenge has not been in a declining global industry; indeed, it is quite the opposite as the global textile industry in 2017 was worth nearly $4000 trillion. The primary challenge has been in the viability of textile education programs with respect to student's enrollment and fund raising or budget's survival, particularly in Europe and North America. In these parts of the world, students select education programs that can lead to careers in their domestic markets, and many students are not willing to relocate to different parts of the world given the political and economic instability in many regions around the world. To make matters additionally complex, more than 40% of the world's production of textiles is in China and few other countries in Asia. These regions are substantially different in cultural and social structures than Europe and North America. Therefore, for textile education institutes in Europe and North America to survive in the next few years, they must go global, and it will be necessary for these institutes to establish branches of their programs abroad.

The textile education programs also need to be modified in such a way that dynamic adjustments of these programs can be made in accordance to the industry's developments. Indeed, a significant trade-off must be made between strictly following the ABET criteria and meeting the industry's demands. The ABET criteria are based on the classic approach of engineering education, which leads to calculus being the top of the pyramid of mathematical background. Most of us engineers by education understand that this model, though may be academically useful, did not fully reflect engineering applied needs. Certainly, calculus and differential equations are critical in many research applications, but as Arthur Benjamin, a famous American mathematician, puts it (Ted Talk, 2009), only very few of us use calculus in a conscious and meaningful way in our daily practices. He calls for a change in the mathematical

pyramid to make statistics the top of the pyramid. Ironically, even the ABET did not realize the importance of statistics except in the last 30 years. Now, in the era of big data and unsupervised machine learning, there is no doubt that statistics should be the top of the mathematic pyramid.

Regarding the industry's demands, today's information technology has widened the base of education in such a way that interdisciplinary education has become a critical necessity. This means that highly specific education programs are likely to give way to more interdisciplinary education programs and joint degrees. A textile engineering program in chemical processing may be attractive to some students who have made up their minds to work in the wet-processing segment of the textile industry, but it will not be as attractive for students who wish to become chemical engineers with ample opportunities to work in a wider range of industries. Similarly, a textile engineering program in product engineering, despite its absolute necessity in the textile industry, will not attract students who wish to become material or mechanical engineers with much wider career opportunities. These critical issues need to be addressed in the schools of textiles around the world; a discussion that may very well result in changing undergraduate textile engineering programs to joint programs with other engineering disciplines.

Another line of thought regarding textile engineering education is toward moving to graduate degrees such as master or PhD degrees in textile engineering and restricting undergraduate degrees to textile technology. This change needs to be made in timely fashion before it becomes inevitable. This can indeed result in a wider attraction to students who graduated from different traditional engineering programs such as chemical, mechanical, or electrical engineering. It will also satisfy the current and future trends in the textile industry in terms of many new directions such as the needs to minimize the industry adverse environmental impacts, the strong trend toward more sustainable products, and the utilization of smart technology and nanotechnology in the make of textile products. These areas require higher levels of education beyond the undergraduate level.

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Evolutionary aspects of product development in the textile and fashion industry with respect to marketing changes

2

2.1 Introduction

History lessons can provide a great deal of insight of the present time not only because evolutionary developments do not start from vacuum but also because human progress is largely a cyclical phenomenon, and no matter how progressive the world will become, human approaches to do things will inevitably be recyclable, perhaps in different forms but essentially identical in principle. Ever since the first human stepped on the face of the earth, he created necessities for living such as food, clothing, and convenient environment that we now call goods, products, or services. Yet, when the term product development is mentioned today, it would sound as a new thing that we learn about for the first time. Indeed, this term was used as an independent organizational approach in the late 20th century; nine centuries after the term "engine" or "engineering" was coined, and two centuries after the term "technology" was fully recognized and utilized.

If the term product development was used in the 19th century, it would have rightfully implied an engineering or technology job. At that time, product development primarily meant a process of improving existing products or converting new ideas into innovative products through appropriate design conceptualization and design analysis, which are typically engineering tasks. However, in today's competitive market, the concept of product development has been expanded to accommodate and integrate critical product-related aspects such as consumer's perception, product's attractiveness, value appreciation, market niches, environmental and safety factors, sustainability, and anticipated performance over a product's life cycle. These aspects are extremely complementary to the design process, but classic engineering education often ignores these aspects as a result of focusing on product functionality and performance characteristics. Therefore, a job description of a product developer today is no longer restricted to engineering background, and it may indeed cover a wider range of disciplines including business, marketing, logistics, consumer's research, technology, and engineering qualifications [1–3].

In this chapter, evolutionary aspects of product development are briefly reviewed as it would take an independent book and multiple authors to cover the details of these aspects. This is because product development as we know it today integrates all element of a complete marketing network, which primarily aims at maintaining a continuous stream of products that exhibit better attributes and provide newer

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performance features at a faster time-to-market pace. Therefore, this review will only account for product development with respect to marketing changes over time.

Historical marketing changes can be roughly divided into five phases [4–8]: (1) the customization era, (2) the production-focus era, (3) the product-focus era, (4) the consumer-focus era phase I (sales), (5) the consumer-focus era phase II (marketing), and (6) the information-focus (societal marketing) era. These eras cannot be described by an exact historical timeline of specific transitions; instead, they represent gradual and overlapping transitions. Indeed, all product development approaches associated with these marketing transitions still coexist in many countries even today.

2.2 The customization era

The customization era goes back to the first human on earth and extends from the ancient time to the industrial revolution of the 18th century. In this era, virtually, all products were handmade as powered machines were yet to be introduced. This was the era when humans had plenty of time to think and reflect on the environment of living things and realize that the earth is the only accessible human's environment. Human also realized the limited capacity of the earth environment to provide space, food, shelter, and energy.

Going further back in history, the earliest customization era was more of an "accustomation" era since it was all about familiarization, acclimation, adaption, and acquaintance with the natural resources of that period. This was the era of largely passive development described by historians at the "hunter-gatherer" era. In other words, humans in "accustomation" era were not ready to create and develop, only to survive with whatever was available. Basic living things such as food, shelter, and body covers were not developed; they were rather discovered.

Some archeologists suggested that humans in the very early years did not wear clothes and only relied on human hair as a body heat stabilizer to control the absorption of heat energy by the naked human skin in hot environment and the loss of heat in cold environment. This means that any human effort to develop artificial body covers, or what is now called "clothing," must have come after early humans lost their body hair. Genetic data suggest that body hair was lost about 1.2 million years ago [9]. Although a single human still grows over 1000 km of hair on average over his/her lifetime, this is far less than the millions of kilometers of hair that a human grew in the early time. Interestingly, what remained of body hair today is a trillion-dollar business around the globe in the form of hair care products, wigs, and hair extensions. In addition, human hair is a critical element in forensic science via DNA, fiber identification, and protein analysis that can assist in investigating numerous crimes [10–12].

One of the first documented forms of product development in the customization era was the making of clothing, which can be traced back to the Mesopotamian era (3500 BC) and into the ancient Egyptian era. One of the earliest fibers used by human to make clothing was linen fibers. Most textiles in the Ancient Egyptian era were

woven fabrics made primarily from linen. The choice of linen fibers by the Ancient Egyptians (3000 BC) was perhaps a result of the lack of other fibers available. Fortunately, linen clothing absorbs moisture very rapidly, but it also dries quickly, making it comfortable fabrics for warm climates. The task of extracting linen fibers from the flax plant required a great deal of know-how [13–15]. To separate linen fibers, flax must be fully retted or soaked in water or chemicals (alkali or oxalic acid) to soften it by loosening the pectin or gum that attaches the fiber to the stem. The process of retting had to be performed very carefully since too little retting may not permit the fiber to be separated from the stalk with ease and too much retting or rotting will weaken fibers. Upon retting, the flax plants must be squeezed and allowed to dry out before undergoing the so-called breaking process in which the decomposed stalks are crushed using fluted rollers that break up the stem and separate the exterior fibers. This process breaks the stalk into small pieces of bark called shives. The shives are then scutched using rotating paddles so that the flax fiber can be completely released from the stalk. It is the author's opinion that the Ancient Egyptians who built the great Pyramids of Giza had also developed the first technology of natural fibers extraction or at least set its underlying principles.

One of the interesting questions that are often asked in the context of product development is what would make humans think of plant fibers and animal hair instead of recycled human hair, which is abundantly available even today, in making clothes? This is a good question for archeologists and historians that the current author is not qualified to answer. One speculation may stem from the high propensity of human hair to attract external parasites, which are both irritating and harmful to human body. Ironically, Alix Bizet, a French student in the Design Academy Eindhoven in The Netherlands recently designed clothes made of human hair (https://www.vice.com/en_us/article/yp55aw/a-dutch-student-is-making-clothing-out-of-human-hair). Whether one agrees with this fashionable approach, the French student tried to follow a logic that was never considered by any product developer in history.

The rest of the ancient history in developing customized textiles made from natural fibers is well documented in the literature. However, in the context of product development, the story of silk was quite unique [16,17]. Ancient Chinese were the first to discover that silk can be made into woven fabrics (3000 BC). They cultivated silkworms and invented the reel and loom required. The mysterious technology at that time involved in making silk fabric led to a Chinese monopoly of silk production for more than three millennia (until about BCE 200) during which smuggling silkworms across the Chinese boarder was a crime of death penalty. The luxury texture, softness, and luster of silk fabrics made it very popular around the world. The famous story of lucrative trade route known as the "Silk Road" was a result of the high demand for silk in the western world, which led to taking silk westward and bringing gold, silver, and wools to the east. Indeed, silk was considered as even more precious than gold. For this reason, the 4000 miles silk journey from Eastern China to the Mediterranean Sea was surely worthwhile. Later, a handful of Chinese immigrants went to Korea and transferred the silk technology with them, and from there, it was spread to India, Japan, and other parts of the world. By the 13th century, silk had entered Europe, and Italy had gained dominance in silk production.

Unfortunately, the secrecy surrounding the production of silk fabrics for 30 centuries had masked documentation of the evolution of this technology. By the 19th century, the interest in silk began to fade away as a result of the large production of cheaper Japanese silk, especially driven by the opening of the Suez Canal, and by the middle of the 20th century, the glory of silk fabrics was substantially vanished with the introduction of synthetic fibers that were initially developed to mimic silk fibers. Now, China is back to be the leading producer of silk around the world (about 146,000 metric tons annually), but the excitement and secrecy have gone forever.

Many historians use fashion and clothing as evidences of the early human realization of the concept of product development. Seven thousand years ago, ancient Egyptians pioneered the early concepts of product development through wide varieties of clothing for men and women that can be observed in the engraved arts on the ancient Egyptian walls today [17,18]. The common men's garment was called the "shenti," wrapped around the body at the waist. Some versions had cords attached to tie the garment, and in other versions, the fabrics are knotted at the waist or held up with a knotted cloth belt. This fashion was later evolved from a short, form-fitting kilt to a longer kilt, extending to the knee and then to the ankle. The paintings on the walls also indicate that Egyptian men often wore no shirts or simple shirtlike garments with their shenti. In later dynasties, some Egyptian men wore a tunic reaching to the knees over the shenti. This was borrowed later by the Roman's empire for working people. High-ranked scribes and many women in ancient Egypt wore long robes, called "kalasiris" usually in white linen. Egyptian clothing for women also included a form-fitting sheath. These are all evidences of the leading role the fashion industry played in the early time of the customization era.

The customization era continued to the time of the industrial revolution of the 18th century. Interestingly, up to the 1400s, the world population was less than 500 million people. By the time of the industrial revolution, the world was still less than 1 billion people. The customization era required high precision of making things and very skilled labor with long experience as these were the main criteria for customer's satisfaction. The relationship between the makers of products and their customers was at the highest level, and the loyalty to certain products was at the same level as the loyalty to product makers. Business competition in this era was very localized, and customers would go extra miles to find the right maker of a product. Advertising was primarily the word of mouth, and skilled product makers were always in demand. In other words, the maker of a product was at the center of business, and customers had to make efforts to find the right makers of the needed products (see Fig. 2.1).

Near the end of the customization era, many businesses were family oriented. This was clearly demonstrated in the textile industry of this era where families worked together at home. They raised their own sheep, which provided wool for spinning and food products such as milk, cheese, meat, and leather. Traders relied on family business a great deal to produce their goods, and this had resulted in economic independence of farmers. In addition, merchants delivered fibers to farms and villages to be spun in homes, which eliminated the cost of building large factories. This social and economic structure was good in this era given the small world population of that time.

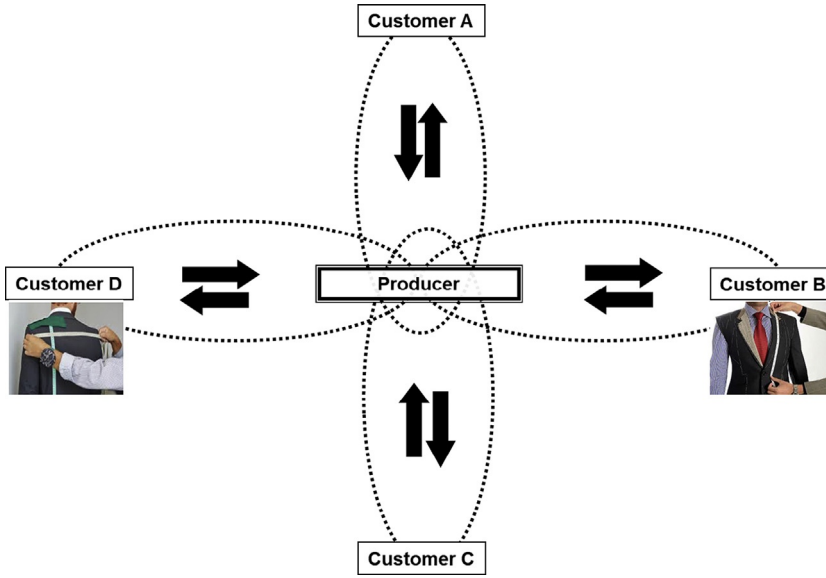


Fig. 2.1 Customization-focus era.

2.3 The production-focus era

The industrial revolution of the 18th century had transformed agricultural societies to more industrialized and urban regions. Machines powered by steam engines started to replace human power in many applications [19–21]. This had resulted in a significant shift toward manufacturing and mass production, which placed machine at the center of business as shown in Fig. 2.2. This era can be described as the production-focus era since the success of any business was primarily measured by production efficiency and cost of manufacturing. It was all about more volume and higher production rates to reduce cost and consequently reduce price. Labor was still intense since machines would not run properly without close supervision and human involvement. Many businesses planned their marketing strategies based on economies of scale, which is the production of more product units to reduce input costs. At the dawn of the Industrial Revolution in the mid-1700s, the world's human population grew by about 57% to 700 million, and by 1800, it reached 1 billion. This trend led to the common assumption that demand will always exceed supply and supply creates its own demand (or if somebody makes a product, somebody else will want to buy it). The theory of increasing demand prevailed, and the world population reached 2 billion people in 1927.

Before the industrial revolution (1760–1840), fibers were spun into yarns, and yarns were woven into fabrics using manual means. The early machine for turning fiber into a thread or a yarn was the so-called spinning wheel, which has an obscure origin. At the beginning of the 16th century, the first semimachined spinning system

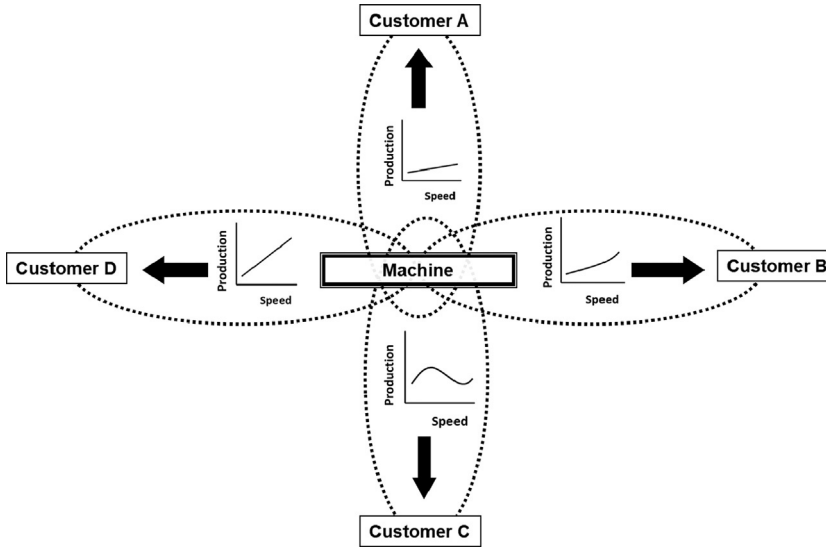


Fig. 2.2 Production-focus era.

called the Saxon, or Saxony wheel, was introduced in Europe [17]. It incorporated a bobbin on which the yarn was wound continuously, and the wheel was actuated by a foot treadle. Ironically, at that time the loom, which weaves the yarn into a fabric, was somewhat ahead in the process of development. This was a classic case of how invention and innovation can be independent of time sequence by virtue of consumer and market demands.

The shortage of yarn supply resulting from the improvement of the loom in the 18th century stimulated a series of inventions that converted the spinning wheel into a powered, mechanized component [17,18]. This development began about 1764 with the invention of the spinning jenny by James Hargreaves, an uneducated English spinner and weaver, who witnessed his daughter Jenny accidentally overturning his hand-powered multiple spinning machine. As the spindle continued to revolve in an upright rather than a horizontal position, he began to think in a different design direction that led to the invention of the spinning jenny with which one individual could spin several threads at one time. Ten years after the introduction of the spinning jenny, an English spinner by the name Samuel Crompton developed the so-called spinning mule. This machine permitted large-scale manufacture of high-quality thread. It was inspired by the problem of excessive defects produced on the spinning jenny and by the weaver demand for a defect-free yarn, but it did not add to the basic idea of the spinning jenny.

On the fiber production side, natural fibers such as wool, linen, and silk were the dominant fibers in the early period of the industrial revolution. Toward the middle of the revolution (1807), a breakthrough occurred with the invention of the first cotton gin by Eli Whitney, an American inventor. This invention dramatically fueled the

momentum of the industrial revolution [22,23]. It transformed the tedious and time-consuming process of separating cotton fibers from cotton seeds into a mechanical process that substantially increased ginning efficiency. This invention resulted in the United States becoming a major contributor to the industrial revolution and boomed US cotton exports from less than 500,000 pounds (230,000 kg) in 1793 to 93 million pounds (42,000,000 kg) by 1810.

The ring spinning machine as we know it today (excluding automation and process control) was invented by the American John Thorp in 1828. It was an invention because the idea of using a ring and traveler was introduced for the first time. By the 1860s, ring spinning had largely replaced Samuel Crompton's spinning mule in the world's textile mills because of its greater productivity and simplicity. In the second half of the 20th century, two new spinning systems were introduced, which accelerated the spinning process exponentially and shortened the spinning preparation process. The first was open-end spinning technology, which was invented and developed in Czechoslovakia in Výzkumný ústav bavlnářský/Cotton Research Institute in Ústí nad Orlicí in 1963. The second was air-jet spinning, which was introduced by the Japanese-based Murata Machinery Ltd. in 1997. The underlying principle of air-jet spinning was derived from an earlier invention by E.I. Du Pont de Nemours and Company in 1956.

The earliest development in loom design was through two revolutionary inventions in the weft and warp direction. The first invention called the flying shuttle was invented in the 18th century by John Kay, British weaver, in 1733 (not to be confused with the spinning inventor Joh Kay of 1767). It was a revolutionary development at that time since it replaced the older shuttle hand insertion by an uninterrupted flying shuttle that carried the weft through the warp threads faster and over a greater width of cloth. The flying shuttle was also able to handle wider looms, which saved a great deal of labor work. The second invention was the semiautomated loom invented by Basile Bouchon and Jean Baptiste Falcon in the period 1725–28 and further developed into a fully automated machine by the French engineer Jacques Vaucanson in 1745. Although these inventions did not materialize into large-scale commercial machines, they represented the sparking basis for the first economically feasible automated loom, called the Jacquard loom in 1801. This was the work of Joseph Marie Jacquard, a French inventor, who demonstrated a loom that enabled unskilled workers to weave complex patterns in silk. This loom was controlled by a chain of multiple cards punched with holes that determine which cords of the fabric warp should be raised for each pass of the shuttle.

In the context of product development, the invention of the Jacquard's technology provided an insight into two factors that still exist today in modern product development: (a) the social effect of product development and (b) technology migration. The Jacquard's technology was a real gain to mill owners seeking higher efficiency and less reliance on skilled labor, but it had also resulted in labor unrest because it put many skilled labors out of job. Technology migration was a result of using the principle of the Jacquard technology in products associated with information technology. The idea of storing and automatically reproduce complex information was never known to human before the invention of the Jacquard's technology. Following this

idea, many analytical engines were created [18,19]. In 1832, Semen Korsakov, a Russian government official, devised methods of searching information stored on punched cards for the Russian Police Ministry. In 1837, English mathematician Charles Babbage described plans to use punched "number cards" to input programs and data into his analytical engine. In 1846, Alexander Bain, a Scottish clock maker, used a "continuous card" in the form of punched paper tape to speed the input of text messages for transmission over the railroad telegraph. Indeed, the propagation of the concept of data storage and input on punched tape remained in use for small computers and machine tool control through the early 1970s. These major developments have led to the initiation of the first and largest information technology company in history, International Business Machines (IBM) Corporation in 1924, which introduced its own punched cards of rectangular holes and 80 columns (the standard data storage medium of its time) to dominate the early data processing industry.

The 20th century came with the arrival of electricity replacing steam machines by big electric motors without removing the pulley system. By 1940, it was realized that the flying shuttle was too bulky and subsequently too slow leading to small number of picks per minute (weft-insertion rate). As a result, the projectile loom was introduced in 1945. This had opened many ideas for weft insertion including the use of air and water jets for weft insertion, which accelerated the loom exponentially and resulted in weaving much broader fabric widths. These technologies became commercially available by 1950, transforming the loom from the era of shuttle loom to the era of "shuttleless" loom. In addition to water- and air-jet insertion, gripper machines employed a small projectile raising a weft from a side supply and taking it to the other side, and rapier machines applied a narrow but long rod moving from a side and picking a weft yarn. Today, all kinds of loom are utilized including the classic shuttle loom, which is still in use in many developing countries.

The next development in loom design was the concept of multiphase loom introduced during the 1970s, wherein all loom tasks occurred simultaneously to generate fabrics at rates exceeding 1.5 yards per minute. In addition, more complex fabric designs are now possible because of the introduction of CAD/CAM or computer-aided design and manufacture technology in 1980s. These developments have reduced the time of the fabric design process from weeks and months to hours.

The invention of the first knitting machine represented another example of a great idea that was dead on arrival because of its impact on social disruption. William Lee of Calverton near Nottingham, England (1563–1614), saw a huge market opportunity when he realized that England's population was approaching 5 million people and market experts of this period estimated that this population needed about 10 million pairs of stockings annually or about two pairs per person. This was impossible to produce domestically at that time since hand knitting could produce only six pairs of stockings a week. In 1589, he invented the first stocking knitting machine, which is considered by many historians as the first major stage in mechanizing the textile industry, 200 years before the Industrial Revolution. Before this invention, hand knitting was widely spread in homes and was even taught in schools. Lee's first machine was a direct imitation of the movements of hand knitters. The idea was based on using a spring, bearded, or barbed needle that were held in a strong iron bed, surrounded by a

huge wooden frame. The needle bed was held rigidly horizontal, and parts of the rest of the machine worked around it. Later, he improved the capacity of his machine from 8 needles per inch to up to 20 needles per inch and produced stockings from wool and silk. The problem, however, was that the world was still living the customization era in which any mechanized invention meant social dissatisfaction and displacement of skilled labor. As a result, Lee's invention was rejected by Queen Elizabeth I of England fearing labor unrest. In the context of product development, the merit of this story is that inventions, no matter how incredible, are likely to go nowhere without marketing opportunities.

It took more than 150 years and the industrial revolution for much further development in the knitting machine to occur as a result of the rising demand for cheaper stockings made of cotton. In 1757, Jedediah Strutt, an English hosier and cotton spinner, invented the Derby Rib machine, which consisted of an extra set of bearded needles that operated vertically, taking the loop and reversing them. This allowed a plain and purl knit to be used and led to ribbing and tighter flexible fabric. In 1802, Pierre Jeandeau patented the first latch needle, which has a right hook and a latch around the axis. This was later improved by Matthew Leo Townsend in 1817. It was much more versatile than the spring needle, and it did not need to be placed horizontally, since the key was the work of the latch itself. As a result, it could be mounted vertically in a machine. This had made it usable in circular knitting machines, which had a great boost during the time of the American Civil War (1861–65) when the quartermaster general of the Northern army decided the quality of its socks and stockings was far better than the frame knits with necessary seams he had been offered (before then, only plain tubes were being made).

Today, the traditional textile industry is still largely production focused, and new development in spinning and weaving technologies are primarily aimed at increasing speeds and minimizing material waste through a great deal of automation and process control. This is because the industry is essentially mass based; raw materials, yarns, and fabrics are all sold by weight. In a mass in-mass out industry, the focus is primarily on maintaining high production rate and minimum material waste. When the fabric is transformed to the cutting and sewing stage where intense labor is required, the importance of production rate and minimum waste becomes even greater.

2.4 The product-focus era

By the beginning of the 20th century, the world was approaching 1.7 billion. More people meant bigger markets and more diversity in consumer needs. It also meant more producers of goods and services stimulated by many developments occurring after the industrial revolution. These changes marked the beginning of the product-focus era in which more emphasis was placed on the quality and the functional performances of products. In the industrial world, many companies installed automated technologies in their facilities, not only for further increase in efficiency but also more importantly for higher consistency in product characteristics. Countries that were famous for their poor-quality products such as Japan and Korea began to focus

more on producing high-quality products inviting famous quality experts such as Edwards Deming and Joseph Juran to assist them in achieving high quality. The product-focus era was associated with different philosophies of quality and many quality strategies including the following: statistical process control (SPC), quality engineering, and six sigma. The problem, however, was that quality was not free and the concept of zero defects initiated by Philip Crosby was too idealistic since many defects were due to inherent design problems that are not solvable, or solutions were too costly to justify higher prices to the consumers [24]. Nevertheless, quality strategies directed the industry to better management approaches of dealing with products.

The center of the product-focus era was the product, and the common assumption was that a high-quality product will automatically draw consumer's interest (see Fig. 2.3). There was only one element missing, which was consumer's input. Indeed, product quality implementation was largely between supplier companies and receiver companies with the latter set the quality standards and the former deliver. The ultimate user of the product was hardly consulted on what constitutes a product value.

The textile industry continued to be a major player in the product-focus era. Throughout the production-focus era (up to the end of the 19th century), the industry relied totally on natural fiber resources (cotton, wool, silk, etc.) to produce massive textiles. In the 20th century, the fiber segment of the industry entered the era of synthetic fibers as a result of major advances and discoveries in polymer synthesis, new spinning methods, and new polymer solvents. The first idea leading to the development of man-made fiber was proposed in the 17th century by Robert Hooke,

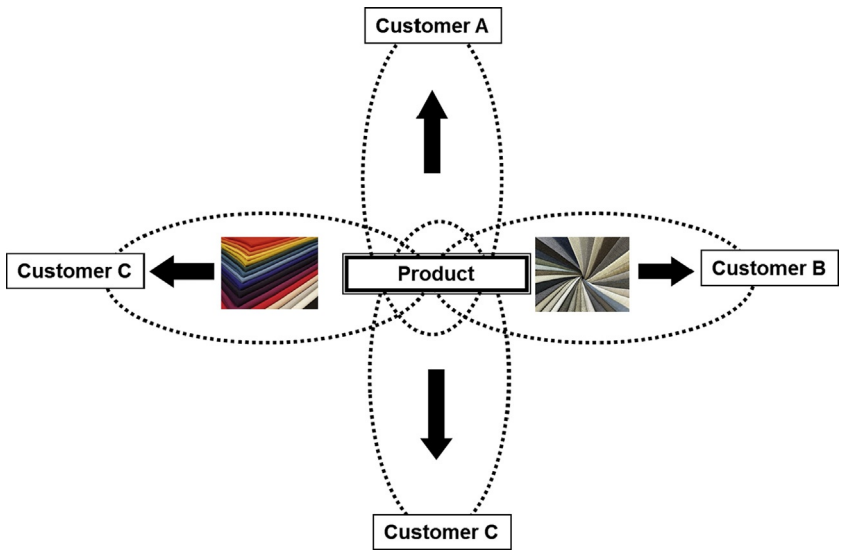


Fig. 2.3 Product-focus era: simple competitive loop.

an English physicist who is more popular for his discovery of the law of elasticity, known as Hooke's law. He suggested that it might be possible to imitate the process by which a silkworm produces silk. Today, this approach is known among engineers and scientists as "mimicking nature." He proposed forcing a liquid through a small opening and letting it harden into a fiber. This was a true creative thinking at a time powered machine was not invented.

The first implementation of the idea of producing synthetic fiber was in the late 19th century. Audemars, a Swiss-born chemist, received the first patent for artificial silk in the 1855. He was able to dissolve the fibrous inner bark of a mulberry tree and chemically modifying it to produce cellulose solution and then using needles dipped into the solution to draw filaments. This was the time before the familiar extrusion spinneret used for rayon fiber, which was discovered later in 1880s by Sir Joseph W. Swan, an English chemist and electrician, who was more famous for his work in developing a successful incandescent light bulb. This was the beginning of a continuous stream of synthetic fiber developments into the 20th century reaching its peak with the development of the revolutionary nylon fiber.

Many historians still remember the New York World's Fair of 1939–40, which was one of the most memorable expos the world had. Visitors of this expo were invited to see what was described as the "world of tomorrow" giving them a first glimpse of wonders such as the television, the videophone, and the Ford Mustang. It was also the first chance to see nylon, the world's first fully synthetic man-made fiber. It was being sewn into pantyhose by a display of knitting machines as two models played tug of war to demonstrate the strength of the fabric. Nylon had been discovered by the Wallace Carothers' group in DuPont's research division 4 years earlier. It was introduced at the fair as the new hosiery "wholly fabricated from such common raw materials as coal, water, and air," which could be made into filaments "as strong as steel." Nylon stockings went on to become a huge success, of course, selling 64 million pairs for DuPont in their first year alone. The introduction of nylon fibers had opened the door for developing and introducing more synthetic fibers including polypropylene and polyester fibers. In 2002, polyester fiber consumption around the world has exceed cotton fibers for the first time in history, and it has continued this advantage until today at higher-than-expected rates. In the context of product development, unlimited performance characteristics can be obtained using synthetic fibers. The production of synthetic fibers also opened the doors for numerous products made from blended fibers, synthetic and natural.

2.5 The consumer-focus era phase I: Sales

Both production and product-focus marketing approaches assumed that the producer of a product knows best, and his/her focus should be on using state-of-the-art technology to produce good-quality products at the highest efficiency possible with the assumption being that this is all it takes for a business to survive and prosper. The missing link in these eras was that the consumers were not consulted on their actual needs of the desired product features. It took almost a whole century for product

makers to recall the customization era and realize that without consumer's inputs, products may be of the highest quality but with no consumer's interest. Consumers were also passive in expressing their opinions on product performance or product diversity as they thought that what was produced represented the best the industry can do and product's performance should be evaluated strictly in view of the face value of a product as described by the producer.

By the second half of the 20th century, the world population exceeded 2.5 billion people, and industrial countries began to witness a significant increase in local competition between organizations making the same product or providing the same service. This has led to more options available to consumers of various products or services. It was also apparent that manufacturing companies can produce far more goods than the market can accommodate. This has led to a more significant role of consumer in the marketplace and a transition of marketing strategies toward focusing on more sales to consumers. Companies began to realize that for consumers to buy more products, they must be persuaded to do so. The primary approach to achieve this persuasion was through heavy advertising of products using different media sources that were also growing in this era. This was the era of forcing products into the hand of consumers through bombarding them with aggressive sales tactics, heavy public advertising, and very costly promotional campaigns. Indeed, many companies in this era elected to spend immensely on advertising at the expense of product development. Furthermore, the competitive advantage of this era was primarily dependent on how big the company in the marketplace and the power of its sales tactic and advertising (see Fig. 2.4). Although all these efforts had targeted the consumers, they were made again after products were developed internally and produced without much feedbacks from consumers.

2.6 The consumer-focus era phase II: Marketing

By the end of the 20th century, it was obvious that the world was undergoing a new marketing phase featured by revolutionary changes in world macroconnections including the following: a world population reaching 5.3 billion people (1990), the beginning of the internet revolution or the WWW era (World Wide Web, 1992) and the new wave of globalization represented by the World Trade Organization (WTO, 1995). Consumers were more than ready to welcome these changes after a period that lasted over 50 years (since WWII) in which they were saturated and tired of hard sell tactics. It was through these revolutionary changes that consumers and consumer advocates were able to send their messages loud and clear of enough is enough of sales push. Businesses also began to realize that simply producing quality products and pushing them onto consumers through heavy attractive advertising and promotional campaigns had exhausted their merits and resulted in consumer's fatigue. Ironically, this realization did not mainly come from large organization since many of these organizations, per the author's opinion, were too big to think and the old wisdom clearly indicates that "elephants cannot dance." The marketing era was largely inspired by creative and talented individuals including Bill Gates and Paul Allen of

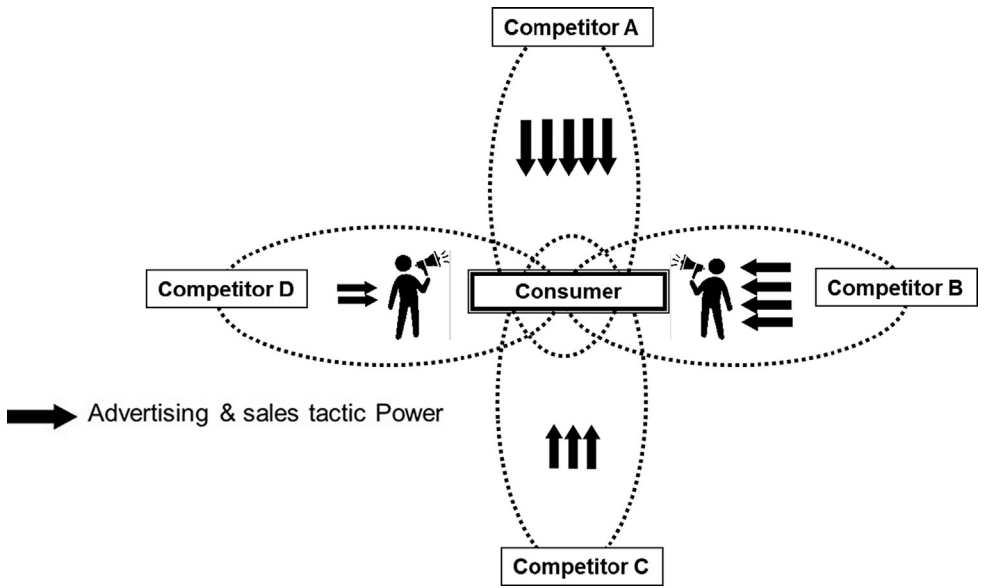


Fig. 2.4 Consumer-focus era: phase I: sales → advertising and sales tactic power.

Microsoft, and Steve Jobs, Steve Wozniak, and Ronald Wayne of Apple who were working since the mid-1970s preparing for the start of this new era.

The marketing era was based on a revolutionary reverse in marketing strategies through true disruptive unusual technologies. The growing world population meant that a true excitement through unusual ideas is needed for developing new products. In addition, companies needed to identify and locate their potential consumers, understand consumer's demographic variables, and realize consumer's needs and wants as opposed to producing products and then trying to convince customers to buy them (see Fig. 2.5). Furthermore, since needs are typically known and wants are not, it was important to induce wants into consumer's interest through creative ideas.

The consumer-focus marketing era was associated with many challenges. Perhaps, the ultimate challenge was to react to the growing individualization of demand yet providing products at the lowest price possible. This had resulted in a substantial transition from mass production to mass customization. In addition, organizations began to realize that they must work tirelessly in different directions including the following: (a) understanding market segmentation, (b) realizing the difference between macro and micro markets, (c) developing parallel approaches for brick and mortar and online markets, (d) establishing market segmentation by demographic factors, (e) establishing a trade-off between mass production and mass customization, (f) performing dynamic competitive analysis, and (g) understanding the true product life cycle. These aspects will be discussed in the next two chapters.

It is the author's opinion that the textile and fashion industry was ahead in the game of product marketing. Since the ancient era, the fashion industry was always about

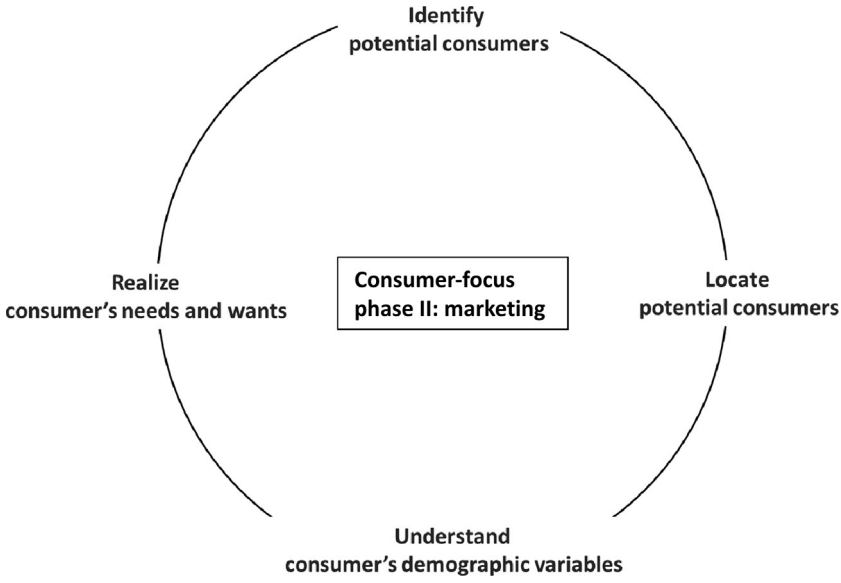


Fig. 2.5 Consumer-focus phase II: marketing.

marketing for human needs, cultures, class, age, and gender. This can easily be seen in the different fashions adopted by different cultures and civilizations from the ancient Egyptian to the Roman Empire to today's modern living. As we move to more recent history, it will only take watching one of the oldest movies ever made, which is "Arrival of a train," a silent movie that lasted 50 s in 1895, to immediately notice the stunning performance of the textile and fashion industry in developing and producing outfits for men, women, and children at a time the train was pulled by a steam locomotive. Compare the outfits in this movie with those displayed in numerous movies over the last 70 years and you will see that this industry has never ceased to develop clothing of different styles, colors, and fits. This was all about marketing with full consideration of consumer needs and wants. Perhaps, looking at the evolution of men's suits [25], one can see how every fashion designer has been inspired by traditional styles at one time or another, meanwhile accommodating generational changes. As a result, men's suit design has evolved from the high conformity and the so-called Ivy League look in 1950s, to the rebellion and individuality look in 1960s, to disco funk style in the 1970s, to the power dressing of 1980s, to the baggy business casual of the 1990s, to the slim-fit and hip-hop style in the 2000s. This evolution clearly indicates that product development is culturally related through presenting contemporary ideas into existing products that accommodate the generational changes without sacrificing the product social or cultural values that most consumers like to adhere to. This concept is known today as "design reinvention [26]."

The new trends of functional fashions have taken product development in the fashion industry upstream, seeking product developments for different applications and different age groups. Now, product developments of functional fashion are creating new markets including the market of intelligent clothing with integrated sensors. The increase in senior populations in many countries has led to the development of clothing just for senior citizens (https://www.huffingtonpost.com/); a category of consumers that has been ignored by the fashion industry for many years. This type of fashion prioritizes comfort and efficiency using customized fits and items that are fitted with magnetic buttons, elastic waists, and thumb holes. Some of these garments are even produced with personalized name tags. It is the author's opinion that functional clothing will certainly place the fashion industry in a leading position in the business world, and one can only imagine going in the direction of clothing for millions of people of special need such as the deaf and the blind with fabric being the platform of compensating equipment, to realize the immense potentials of this great industry.

Another progressively active area of product development in the textile industry is the technical textile segment in which creative designs and R&D represent essential components of success and economic prosperity. The global technical textile market size can reach $300 billion by 2050. It was $160 billion in 2015 and in its way to achieve compound annual growth rate (CAGR) of more than 6% by 2022. Technical textiles are primarily function-focus products; they are manufactured for nonaesthetic purposes to offer numerous functional performances in many areas including the following [27,28]: home-tech products, automobile-support materials, medical and healthcare products, human protection and safety systems, agricultural products,

construction and highway products, filtration, and electronic-support products. Indeed, a quick look at a modern car will reveal that it has technical textiles all over the place resulting in lighter weight and lower energy consumption including the following: seat upholstery, carpets, seat belts, headliners, tire cords, liners, and composite reinforcements for automotive bodies. More examples of technical textiles applications will be presented later in this book.

Product development of technical textiles is typically associated with challenges that are different from those encountered in the traditional textile and fashion industry. These challenges include the following [27,28]: (1) the need for more high-performance fibers, (2) the need to understand the compatibility and interfacial characteristics between fibers and other types of materials (e.g., soil, metals, polymer resin, plastic films, and human organs), (3) the need for different manufacturing models, (4) climbing the learning curve of new manufacturing technologies, (5) the need for interdisciplinary cooperation between textile engineers and engineers in other fields, and (6) the ability to search and discover new market opportunities for technical textiles.

2.7 The information-focus (societal marketing) era

The 21st century began with a revolutionary universal wave of social and information microconnections. At the beginning of the century, Google was recognized as the newest and most capable world search engine, and the Global Positioning System (GPS) began to find its way in the roads and highways of the universe. In 2007, the world witnessed the introduction of Apple I-Phone, Facebook, YouTube, and Twitter. eBay, founded in 1995, began to move globally in the 21st century by building online person-to-person trading community on the Internet. Buyers and sellers were brought together in a manner where sellers are permitted to list items for sale, buyers to bid on items of interest, and all eBay users to browse through listed items in a fully automated way. The items are arranged by topics, where each type of auction has its own category. PayPal Holdings, Inc., which became a wholly owned subsidiary of eBay in 2002, is an American company operating a worldwide online payment system that supports online money transfers and serves as an electronic alternative to traditional paper methods like cheques and money orders. Amazon, which began as an online book seller in 1995, is now the world's largest online retailer. In 2018, Amazon reached 50% of the market share of online retailing, and it became the second company in history to reach $1 trillion after Apple Inc.

The revolutionary information wave of the 21st century was reflected in many marketing aspects. Virtually, all organizations have interactive websites to display their products and services. Today's consumer can navigate through numerous digital content and online information to find the right product in the right time at the right place. Obviously, we are still living this era, and much more will be learned in the years to come. However, it is important to point out that the information-focus (societal marketing) era has brought back all the earlier marketing eras but in a largely digital form. In other words, history is clearly repeating itself in the current marketing era.

Via societal marketing, people can make, buy, and sell products that are personalized and customized to meet the needs and wants of an individual or a small group of consumers. Automation and robotic technologies are now programmed at the highest levels to achieve speed and consistency. Products have improved dramatically both in quality and performance as a result of the immense diversity of consumer needs and wants. Products can also be made via outsourcing and insourcing of various components of the product. Advertising has taken even more abrasive direction as a result of the enormous exposure of consumers to the whole world. Therefore, only organizations that can put all these pieces together will survive and prosper in the years to come.

The contribution of the textile and fashion industry to the information-focus (societal marketing) era is a huge evolution in progress. In recent years, terms such as "wearable technologies," "smart fashion," or "fashionable electronics" are associated with a true revolutionary development in which electronic components are integrated into clothing [29,30]. This development is transforming wearable textiles from merely fashionable products with a primary focus on styles and aesthetics to a combination of styles, aesthetics, and a wide range of functionality. Using wearable textiles, people will wear clothing that can provide critical personal information, monitor important health aspects, communicate with other devices, conduct energy, provide safety warnings, and transform into other shapes or forms to protect the wearer from environmental hazards. Indeed, if you think that clothing today is the most intimate product to human being, simply wait to see a much greater intimacy in the future wearable systems.

In Chapter 1, the need for interdisciplinary effort to design textiles was discussed. This cannot be emphasized enough with respect to smart fashions. Indeed, virtually all engineering disciplines and many other fields will have huge opportunities to participate since the applications of smart textiles require continuing research and discovery efforts in key areas including the following [29,30]: conductive materials, antistatic materials, miniaturized electronics, wireless communication, data transfer, interface systems, material durability, material reusability, product integrity, special coating techniques, physiology, bioenergy, fashion design, fashion engineering, and economics.

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Product development in engineering textiles

3

3.1 Introduction

Today's product life cycle of many products is best described by obsolescence before depreciation. Therefore, for companies to survive and prosper in today's global market, they must sell more products, create new product ideas, and convert their intellectual properties to true market opportunities. Dwelling on the success of a current product will be a short-lived prosperity, and companies must always prepare for the next leading product. Unfortunately, product development can indeed be very risky and substantially costly, particularly when it is not done properly or when it involves major changes in existing operations or requires new technologies. To make matters additionally complex, a product development process, no matter how seemingly organized, may not always result in a product that will draw consumer's interest from the get-go. In the US market, estimates of the failure rate of industrial new products, determined by the significance in return, have increased from about 35% in the late 1980s to more than 50% in the 2000s [1,2]. Estimates of new product failure rates will vary widely by company, product category, and industry. However, competition is tougher than ever, and consumer's choices are hardly predictable.

In general, a failure of a new product can be attributed to many factors [1–5], some of which are marketing related and other are design related. Marketing-related factors may include the following: (1) inadequate market analysis leading to misunderstanding of consumer needs and wants; (2) inadequate cost analysis leading to higher cost and overvaluing a product; (3) strong competitor reaction; (4) delayed or rushed product time to market; (5) targeting wrong markets; (6) existence of similar products at lower prices; (7) too much reliance on the success of existing brands in promoting new products; and (8) other factors associated with delivery, tariffs, safety, and trade regulations. Design-related factors may include the following: (1) using old solutions to design new products; (2) less-than-optimal functional performances; (3) problems with patent, license, or copyright issues; (4) more focus on functionality at the expense of style, appearance, and ease to use; (5) performance and quality problems not foreseen at the design stage; (6) safety issues unaccounted for in the design analysis; and (7) poor coordination between product design and product manufacturing.

In today's market, products are sold to consumers of immense diversity of needs and wants. However, consumer's feedback on the performance of products is often limited to a database reflecting complains or rejects of products due to various types of dissatisfaction. In a typical organization, this database only represents less than 5% of product's users, and it should be taken seriously as it may reveal problems that were not foreseen in the product development stage. However, products are often returned and replaced without a question asked, as a result of the classic business wisdom that

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the "customer is always right." This makes the reliance on returns and rejects a very limited source of information on the actual product's performance. On the other hand, how often would a consumer receive a phone call or an email asking about how they feel about the performance of a product he/she bought a year ago? If a product stays in the possession of a consumer for a year or longer, it could be because the product is performing so well or due to the lack of alternative options, which is normally a matter of time before a new product is introduced. This aspect of consumer's feedback is often missing in corporate database. It is important that market research utilizes "big data" approaches by gathering more information about current product's performance and consumer's desire of areas of improvement. In today's information era, "dynamic consumer feedback" should be a part of any organization marketing database. This type of feedback is timely reflective of product's performance and alone can result in stimulating creativity to produce new products or enhance the performance of an existing product.

Traditionally, product development has been known as primarily an engineering job. This was a result of the common perception that product development is merely a process of improving existing products or converting new ideas into innovative products through appropriate design conceptualization and design analysis, which are typically engineering tasks. However, in today's competitive market, the concept of product development has been expanded to accommodate and integrate critical product-related aspects such as consumer's perception, differences between needs and wants, product's attractiveness, value appreciation, market niches, and anticipated performance over a product's life cycle. These aspects are extremely complementary to the design process, but classic engineering education often ignores these aspects as a result of only focusing on product functionality. Therefore, a job description of a product developer today is no longer restricted to engineering background, and it may indeed cover a wider range of disciplines including nonengineering qualifications.

In this chapter, basic concepts and various elements of product development will be discussed by providing a simplified view of the product development system to familiarize the reader with the basic tasks constituting most product development programs. Key elements of product development will include the following: (1) generating product idea, (2) determining and defining anticipated product performance characteristics and related attributes and requirements, (3) the information-gathering process, (4) evaluating the merits of the new idea to justify proceeding forward, (5) design conceptualization and design analysis, (6) mass manufacturing, and (7) marketing.

3.2 What is product development?

In general, product development can be defined as the process of creating new products with added or different characteristics in comparison with existing products for the sake of offering additional benefits to consumers and maintaining or increasing the profitability of the product's provider. In other words, any product development should result in mutually beneficial outcomes to both the maker and the user of the product. Product development may also be defined as a system with well-defined

inputs, such as specifications of a new product idea or solutions of existing product problems, and well-defined outputs such as measurable beneficial factors such convenience characteristics, product's ease to use, and revenues/profits for product's makers. Both definitions constitute the typical journey of product development in most organizations.

The complexity of today's product development process is reflected in many iterative aspects most of which are implemented without guarantee that the product will ultimately be attractive to consumers. It involves many disciplines including engineering, manufacturing, market research, marketing, safety and regulations, business, sales, and accounting. The common focus of all these disciplines is always the consumer or the buyer of the product. Therefore, each discipline must operate based on - forward-thinking and backward projection (user feedback) analysis. This makes product development essentially an iterative process. Based on actual case studies of product development in which the author was a contributor, a typical product development journey may involve the following dozen steps [4,5]:

1. Identifying product's idea, feasibility, benefits, cost, and potential market value
2. Approval of the idea
3. Conceptualizing and designing the product
4. Establishing product development time frame and roadmap in view of product's urgency or time-to-market speed and the demographic distribution of potential consumers
5. Developing a viable product's model or prototype: design and resources allocation
6. Testing the product prototype internally within the organization and externally through trial user's inputs
7. Iterating based on testing outcomes
8. Evaluation of product safety and sustainability
9. Iterating to meet safety and sustainability regulations
10. Approval of product model release
11. Developing a strategy for the conversion of product model to mass production
12. Launching of a wide-spread advertising and promotional campaign of the new product

The previous steps only represent one example of many approaches that different organizations may take depending on their management structures, resources, competitive status, and vision. However, they all begin with the ultimate challenge of identifying product's idea, which is feasible, beneficial, and cost-efficient and has rewarding potential market value. This task does not come via an administrative order or a formal process but rather from a distributed leadership mobilized by motivation and stimulated by creativity.

3.3 Where to begin and who should be responsible for product development?

The critical question, which is often raised, is where to begin? and who should be responsible for product development in an organization? The answer to this question should be made in view of size and resources of an organization. Large organizations will typically have the resources and the personnel that allow highly

organized and coordinated product development projects. Small organizations can only rely on creative individuals to develop products given their limited resources. Common differences between the approaches of product developments by these two types of organization are discussed in the succeeding text. These differences are represented by some typical examples of what large and small organizations do; they cannot be generalized, and they do not reflect standard approaches.

3.3.1 Product development in large organizations

Large organizations typically rely heavily on the research and development department (R&D) in creating new product ideas. According to the Business R&D and Innovation.

Survey (BRDIS) [6,7], companies active in research and development employed 1.5 million R&D workers in the United States in 2013 (just over 1% of total business employment in the United States). R&D employees are defined in the BRDIS as all employees who work on R&D or who provide direct support to R&D, such as researchers, R&D managers, technicians, clerical staff, and others assigned to R&D groups. Two-thirds of businesses' R&D employees in the United States were scientists, engineers, or R&D managers, and the remainder were technicians or other support staff. The three largest industry groups in terms of domestic R&D employment in 2013 were software publishers, pharmaceuticals and medicines, and semiconductor and other electronic components.

Common tasks of R&D divisions can be divided into three main directions [8–10]:

(a) Basic research for the sake of understanding fundamental aspects associated with products and processes. The outcome of basic research may not have a direct impact on practical or commercial applications, but it certainly provides the necessary knowledge base that should be available in any product development project including constraints and boundaries associated with raw material properties, processing techniques, and the relationships between material attributes and product performance characteristics.

(b) Applied research to meet specific objectives associated with the development of a product. This type of research requires an interdisciplinary approach to cover all facets of product development. It should be integrated enough to include forward-thinking and backward projection analysis. The outcome of applied research could have significant practical or commercial applications.

(c) Development tasks to create the necessary knowledge for engineers that is used for converting research findings into physical or virtual product prototypes.

In view of the previous tasks, a research and development (R&D) department in a large organization can be very beneficial in the process of product development. However, two critical factors should be considered in establishing and operating a R&D department: (1) the cost associated with R&D and (2) productivity of R&D department. These factors are discussed in the succeeding text.

The cost associated with R&D has been in the center of attention of many large organizations. Indeed, this cost is often considered as one of the secret recipes that many organizations would not reveal or if they did, it would not be in absolute values but rather as a percent of total expenditure for the sake of product promotion and

advertising. This is due to the idealized presumption that R&D spending should be connected to increased innovation, revenue growth, and profits. Unfortunately, organizational data reported annually revealed that there is no long-term correlation between the amount of money a company spends on R&D and its overall financial performance. Instead, what matters is how companies use that money and other resources, as well as the quality of their talent, processes, and decision-making, to create products and services that connect with their customers (https://www.strategyand.pwc.com/innovation1000). The problem, however, is that without R&D, an organization may be taking a huge technical risk as it will likely lack the necessary knowledge base to develop new products. On the other hand, excessive spending on R&D may result in high costs (market risk) specially when product ideas are unsellable. This point is particularly important in large corporations in which R&D expenses can easily run into billions of dollars. These high expenses are typically witnessed in healthcare and pharmaceutical firms and in large technology corporations that reinvest a significant portion of their profits back into R&D to maintain their technological growth.

The issue of R&D productivity is also a serious one. R&D departments do not produce physical products, and they are not intended to bring direct revenues. Yet, they are expected to perform in systematic fashion like production personnel with the expected results being at best the production of intellectual properties in the form of patents or copyrights. In other words, the main product of a R&D department is knowledge and information that may potentially lead to product models and innovation. There are no statistics on what percent of new product ideas is generated in R&D departments versus outside sources, but a rough analysis by the author revealed that with respect to the complete A-to-Z product development process, the R&D contribution may be at best an A-to-G contribution (or nearly 30% contribution). This is due to that fact that many organizations have hundreds, perhaps thousands, of intellectual properties that were produced within the R&D capacity, but they have not been materialized into products because of other limitations associated with feasibility, timing, and current market reception.

Some organizations establish R&D departments injected with heavy engineering staff with the hope that somehow R&D capacity can be extended to the A-to-Z status of product development, thus making R&D more productive in terms of product development. However, the success of this approach will largely depend on understanding the differences between the roles of engineers and scientists in product development. Engineers cannot be described as scientists, and scientists cannot be described as engineers. Even when their ultimate goals are identical, their approaches are fundamentally different. The following points summarize the differences between engineers and scientists [4,5]:

- In general, scientific knowledge informs engineering design, and many scientific advances would not be possible without technological tools developed by engineers.
- Engineers have many common attributes: they are typically people of few words, lots of stress for fear of failure, and lots of thinking and careful actions. Scientists on the other hand are often vocal and unconstrained thinkers, and they often think out loud.
- Unlike scientists, engineers cannot be very aggressive in attacking a problem as it is often less costly and less risky to research than to reengineer.

- A scientist is always searching for knowledge, while an engineer is always searching for a specific outcome through knowledge.
- Some scientists see things that relate to virtual things with the hope that some things will turn out to be the real things; those are called visionaries. Engineers see things only when they yield other visible things. As a result, many scientific breakthroughs are results of picking and choosing of pieces that were created for an unintended puzzle. On the other hand, things must break for engineers to achieve breakthroughs. In other words, engineering breakthroughs often occur as a result of failure of existing products.
- Most scientists focus on identification and verification of physical phenomena; engineers benefit a great deal from these efforts to bear on practical problems.
- All engineers typically work and perform under some sort of pressure; they are not free to select the problem that interests them; scientists are.
- Both engineers and scientists use a reasoning process to diagnose and solve problems. However, an engineer must learn to react efficiently to a predictable or an unpredictable problem, as problem-solving represents an essential engineering task. Scientists on the other hand spend more efforts exploring the problem than solving it.

The differences previously are intended to demonstrate the complementary roles of engineers and scientists and not to segregate between the two. They can all be summarized in one word, which is "speed." In the engineering world, speed is the most critical dimension of doing things because of the time-to-market pressure. In the science world, a researcher has all the time in the world to think and explore. When a researcher is put under time pressure, he/she becomes a consultant, and only very few researchers can do that as this requires descending from the research high tower to the heat of the real world. Nevertheless, it should be realized that a great deal of today's common knowledge among engineers and product developer has been a result of past scientific research, and many of today's scientific research may become the sparking point for future innovations.

In addition to R&D divisions, some large organizations may have an independent product development division, which is typically headed by a product development director. This is perhaps one of the hardest jobs in an organization as it requires a multiplicity of skills and knowledge including the following: creative and critical thinking, problem-solving ability, business insight, awareness of existing products, understanding of materials, awareness of market needs and wants, knowledge of computer-aided design (CAD), computer-aided industrial design (CAID), and graphic design. A product development director will typically oversee the design and the redesign process of a product, manage and coordinate efforts made by interdisciplinary teams, match new product values with cost limitations and marketing data, observe and evaluate testing outcomes, evaluate product manufacturing facilities, and continuously meet with potential clients and product users. These skills may point at a candidate of engineering background, particularly, given the fact that he/she should be able to read blueprints, understand design conceptualization plan, and express opinions about engineering and manufacturing issues. However, a combined education of undergraduate engineering and a master of business administration (MBA) are often considered as essential qualifications for product development directors if they had some years of experience in marketing and product development activities. Some schools also offer a master in product design development, which lasts about

1 year after an undergraduate degree in engineering (https://design.northwestern.edu/product-design-development-management/).

3.3.2 Product development in small organizations

One of the common phenomena witnessed in the second half of the 20th century and into the 21st century was the creation of small business organizations that have become exponentially big in a short period of time, either through acquisition by large organizations or by ultimately displacing large organizations [11]. The luxury of being a small business stems from the fact that it is typically initiated by a small group of highly motivated individuals that come together for the sake of disrupting the traditional technology through creative big ideas. Those individuals are typically not worried about solving existing problems, creating a chaos in a current operation, or tarnishing their reputation, as they are totally unknown to begin with. Their primarily concentration is on their own ideas and how to go about converting them into products given the limited time and resources they have. They also know that there is no second chance and failure could mean ceasing their dreams forever. In Chapter 2, many examples were presented of creative individuals who started their own business in the textile field and developed machinery and technologies that have led to the world as we know it today. In recent history, the story of the two friends Bill Gates and Paul Allen who found Microsoft in 1975 and the story of Steve Wozniak and Steve Jobs who created Apple computer in 1976 are both evidences of small business that have become so big that are now ruling the world in many aspects. Those incredible people did not have a product development roadmap to work with, and they did not even conceive that their product ideas will alter the world and transform it into a totally new world, but they surely knew that they were into creating very different products. For these reasons, the best we can learn from their experiences is that ingenious product ideas primarily stem from individuals who are free from many of the formal administrative bureaucratic procedures.

3.4 Product development: System, process, and cycle

In describing product development, engineers use terms such as "system," "process," or "cycle." Product development may be identified as a system because it involves key inputs and yields well-defined outputs. Within the system, there are many processes or phases of work that must be done properly to develop a satisfactory product. The dynamic nature of any product development system and the inevitable need to revisit some of its phases make the use of the term "product development cycle" a better way to describe any product development endeavor. A product development cycle can be defined by seven critical phases that can collectively lead to an economically sound product and assure optimum product performance. These phases are as follows [4]:

1. Generating product idea
2. Identifying performance characteristics and related attributes
3. Information gathering

4. Merits and justification
5. Design analysis leading to a product model
6. Mass manufacturing
7. Marketing

These phases are illustrated in Fig. 3.1 and are discussed in the following sections.

3.4.1 Generating product idea: Invention, patenting, innovation, and dissemination

The sparking point of initiating a product development cycle is the discovery of an idea, which is worthy of further consideration for developing a new product or modifying an existing product. The process of generating a new idea may vary from one organization to another depending on the source of idea, the type of product (physical or service), and the target market. In this regard, it is important to distinguish between four common terms used in generating product ideas: "invention," "patenting," "innovation," and "dissemination." In the engineering world, invention and innovation are distinctly different; invention is to conceive a new concept or an idea, and innovation is to convert the concept or the idea into a real product. Obviously, to innovate, you must invent, but innovation is best determined by the sum of invention, customer value, and business model. Dissemination, on the other hand, is a subphase of the innovation process but at much larger scale; it implies a massive, efficient, and cost-effective use of an innovation [12–15]. Patenting is a concept that can be traced back to the 18th century. It is the traditional legal way to assure the novelty or the authenticity of an invention. A patent right is a certificate of grant by a government of an exclusive right with respect to an invention for a limited period of time. In the United States, for example, a US patent confers the right to exclude others from making, using, or selling the patented subject matter in the United States and its territories. An essential substantive condition, which must be satisfied before a patent is granted, is the presence of documentation of patentable invention or discovery. To be patentable, an invention or discovery must relate to a prescribed category of contribution, such as process, machine, manufacture, composition of matter, plant, or design.

The root of an idea may not necessarily be an engineering work, and it may not even be about adding new functional features to a product. The success of an idea can be solely due to some attractive features that have nothing to do with any added value, except the satisfaction of social or cultural interest. In the textile market, many ideas came about by a shocking discovery of a whole new concept of clothing. For example, who would have ever thought that an utterly ridiculous concept such as "ripped jeans" would have become a consumer's obsession. Now, you can barely walk anywhere without being shocked and stormed by torn knees and ripped threads in a pair of denim jeans that may be worth more than $200. Even the German developer of the original jeans, Loeb Strauss, or Levi, would not have conceived that this would ever happen to his product when he developed it in 1870s. The intention was a twilled durable cotton cloth that would suit the working man (the potential consumer), and now, it is a symbol of rebellion and an expression of anger toward traditional universal societies.

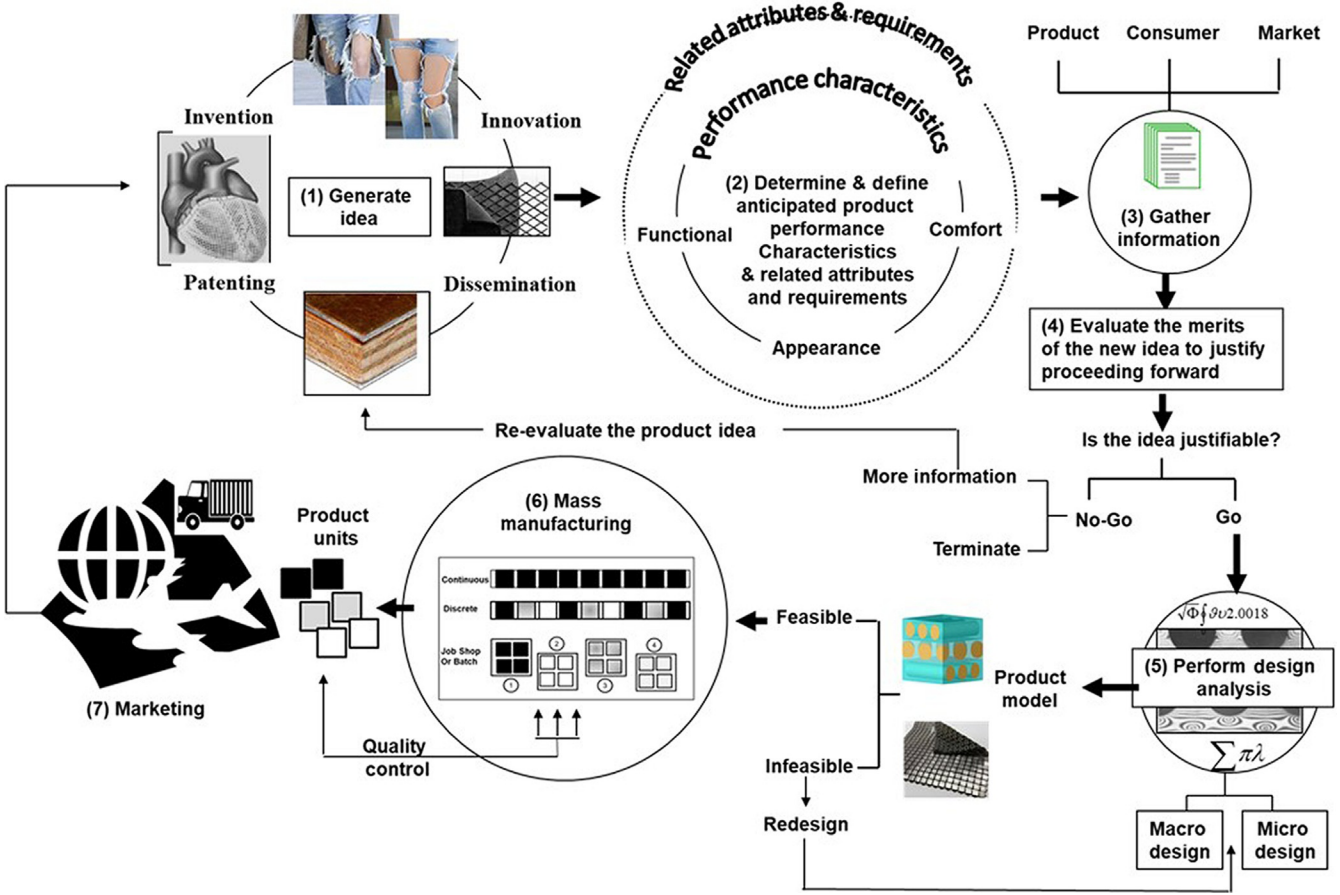


Fig. 3.1 Basic steps of product development.

The idea of ripped jeans was also generated from social origins in 1970s. In the 1960s and 1970s, the lower-end segment of working class was wearing jeans on daily basis. This has meant many torn jeans being seen frequently among this class. This was not for showing-off fashion but rather because this class could not afford buying new denim. Per the author's opinion, this provides a unique and fascinating concept of generating new product ideas. Indeed, one must ask the logical question of the fate of billions of textile products including garments, utility items, and shoes that are being disposed by the billions of consumers every year. Perhaps, the ripped-jeans idea can stimulate thinking in this regard, which provides more economical advantages over the traditional ideas of recycling via shredding of old items and tedious costly processes of fiber separation. Indeed, the old country song by Dolly Parton, titled "Coats of Many Colors," can set the stage of a new era of generating product ideas using what can be called "the destitution to innovation" model, or perhaps, the "Parton" model:

> *Back through the years I go wanderin' once again … Back to the seasons of my youth, I recall a box of rags that someone gave us, … and how my momma put the rags to use … There were rags of many colors, but every piece was small, and I didn't have a coat, and it was way down in the fall … Momma sewed the rags together … Sewin' every piece with love … She made my coat of many colors … That I was so proud of.*

As will be discussed in Chapter 6, the previous words may constitute the ultimate way to resolve the global sustainability resulting from the huge consumption of today's fast fashions and its impacts on the environment and human well-being. Obviously, one would say that a crazy idea like ripped jeans could have been initiated by the consumers by ripping their own jeans. However, today's denim is different than Strauss original lighterweight denim; it is made thicker, stiffer, and rip-propagation proof even upon harsh repeated use or multiple washing and drying. This means that to create ripped jeans, a predesigned technical distortion of fabric must be made, which represents the ultimate concept of disruptive technology, one of the common terms used today in product development.

A product idea can also stem from the need to improve the performance of existing product categories due to apparent design deficiencies. This situation is more common in technical textiles than traditional textiles. For example, the initial design conceptualization of safety airbags was primarily focused on the timely deployment mechanism of an airbag at the moment of car collision [16,17]. However, some safety deficiencies in the airbag model were discovered, not at the product development stage, but after airbags were widely used in many automobiles. These deficiencies were so serious that now the option of turning off an airbag is installed in all modern cars. Another famous example of technical textiles is the bulletproof vest, in which the inherent deficiency stems from the trade-off between functionality (ballistic resistance), and comfort (light weight). As will be discussed later in this book under the subject of "ballistic protection," the design of bulletproof vest has undergone many changes to optimize this trade-off [18–22]. A more recent product idea implemented in the late 1990s was to replace Kevlar (a very strong aromatic polyamide (aramid)

threads with a lighter, more flexible, and stronger fiber). The choice was Zylon fiber made from a liquid-crystal polymer (poly(p-phenylene-2,6-benzobisoxazole) or PBO). The new product was called the "the wonder fabric," and it was widely used for law enforcement ballistic vests until 2003 when two shooting incidents involving Zylon vests resulted in the death of an officer in California and serious wounding of an officer in Pennsylvania. At this point, the National Institute of Justice (NIJ) decertified the "wonder fabric" for use in law enforcement ballistic vests, particularly after discovering that Zylon fibers rapidly degraded, especially under hot and humid conditions.

3.4.2 Identifying performance characteristics and related attributes

Once a product idea is conceived and tentatively accepted, the next step of product development is to determine and define the anticipated performance characteristics of the intended product. For textile products, the primary categories of performance characteristics include functional characteristics, comfort, and appearance. Under each category, one can list many examples of performance characteristics. For example, functional characteristics may include durability, waterproof, and bulletproof. Functional characteristics may also be described in terms of supporting characteristics that must be available to support the main functional characteristics. One common example of supporting characteristics is interfacial characteristics. These describe the surface compatibility between textiles and other objects that may come into contact with textiles such as soil, human organs, and metals. Comfort characteristics may imply thermal comfort or tactile comfort. Appearance characteristics may imply texture, style, fit, and color.

As can be seen in the previous examples, some performance characteristics cannot be measured or tested directly since it is typically a function of many measurable attributes with associated thresholds that must be satisfied in the product to meet its intended performance. For example, the main performance characteristic of a fibrous product may be determined as "durability." However, durability per se is not a measurable characteristic, and it must be specifically defined. It may be defined by the ability of a product such as military uniform or mine working uniform to withstand external stresses resulting from possible harsh physical actions and environmental exposures. In this case, related attributes will be those of the components constituting the product (i.e., polymer, fiber, yarn, fabric, and final assembly). These attributes may include the following: fiber strength, yarn strength, yarn structure, fabric tear, bursting strength, UV resistance, or heat resistance. These are well-defined and measurable parameters with values that can be considered in the design analysis of the fibrous product.

In general, product functional performance characteristics and corresponding attributes will depend on the complexity of the intended product and whether it is a modified version of a preexisting product or a totally new product. For example, a fibrous surgical implant may be described in terms of two basic functional

characteristics: durability and biocompatibility. The former is typically related to a set of attributes such as filament tensile strength, load-bearing capacity, decomposition resistance, and fiber weight. The latter is commonly related to another set of attributes such as polymer type, chemical compatibility, and fiber surface morphology. Other performance characteristics such as allergic risk and X-ray transparency may also be considered. These medically oriented functions must be considered in the choice of fibrous material and the design analysis. On the other hand, a traditional product such as knit outfits may be associated with specific target functional characteristic such as dimensional stability. In this case, related attributes may include the following: shrinkage upon washing and drying, fabric twisting, and fabric creep.

Today's product performance is increasingly determined not only by the basic intended performance characteristics but also by other factors that are not directly related to its functionality within its expected life cycle. This makes the process of defining these characteristics and determining related attributes more challenging. For example, a textile product may exhibit high-functional performance, yet it may have been developed and produced using unsustainable means including the following: using excessive water, wasted chemicals, or nonrenewable resources in its dyeing and finishing or using fibers that have been characterized as unsustainable. Indeed, most high-performance man-made fibers are made from synthetic polymers; the feedstock of which is unsustainable oil based and most natural fibers use high consumption of water and land. As more environmental impacts are witnessed, consumers will become more aware of these issues, leading to their inevitable inclusion in the product development process.

3.4.3 Information gathering

In today's competitive market, a successful planning of product development must be based on three key elements that we call "the 3Ps." These are the following: product specifications, potential consumer, and potential market. Analysis of these three elements should yield reliable estimate of the product life cycle (see Fig. 3.2). As will be discussed later in this chapter, a product life cycle should not be merely a profile to observe, it should rather be a profile to predict in advance, given the fact that products can indeed become obsolete before they depreciate. Depending on the product idea and the identified performance characteristics and related attributes, a great deal of effort must be made to gather all types of relevant information that are related to the 3P elements. This is a critical phase of product development as it will determine whether the product development cycle should continue or be ceased.

With regard to product information, many information can be gathered about the intended product, some of which may be basic information and other may be highly specific depending on the product complexity. Product information cannot be completed without addressing the following basic questions:

- Is the product's idea truly new and unique?
- Will the idea add value to that already provided by current products?

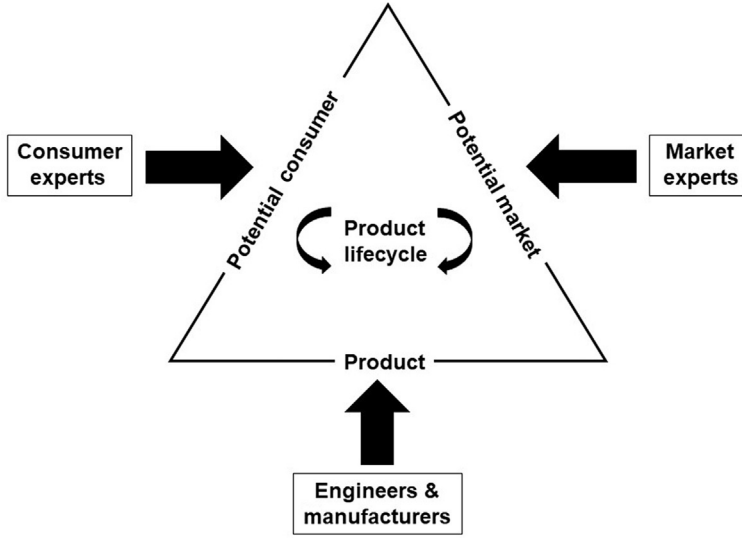


Fig. 3.2 Key product planning elements: the 3Ps.

- If the answer to each of the previous questions is yes, the next question should be: what are the basic requirements and measurable attributes that identify the intended performance characteristics of the product?

Product information is typically technical questions, and they should primarily involve design engineers and manufacturing experts. In case of traditional fibrous products, basic information may include the following: fiber type, fiber attributes, yarn structure, yarn attributes, fabric construction, fabric attributes, processing parameters, and type of manufacturing. Specific information is typically driven by the target functions of the product. Primary sources of information will typically include existing patents, specific technical information of similar products, some research literatures, and expert opinions.

Information related to potential consumers should stem first from the product idea to see whether it was driven by consumer demand, or it is one of those ideas that have never been tested before. Consumer-driven products are typically highly predictable, and market research associated with these products is normally straightforward. In this regard, consumer information should address many common questions including the following:

- Would potential consumers appreciate the added value in the new product? Would this appreciation be reflected in willingness to pay higher prices?
- Would new colors, styles, designs, and fits draw more consumer's interest?
- Is there a trade-off in product performance characteristics that may limit or hinder consumer's appeal (e.g., functionality and comfort)?
- Would factors such as gender, age, and ethnic background influence consumer's interest?

When the product idea is totally new, additional common questions may include the following:

- What is the degree of uncertainty associated with consumer's interest in the new product?
- Will the new product fit in the target consumer's society?
- Are there consumers' cultural aspects that must be taken into consideration (beliefs, traditions, etc.)?
- Would the new product be associated with a costly promotional campaign to drive the consumer's interest?

The previous points are only examples of many questions that should be addressed in the process of information gathering. Obviously, many more points may drive the information-gathering process depending on the specificity of the product. It is also important to point out that consumer information should be gathered and analyzed by consumer experts in the product development team or outside experts.

Information related to potential markets is critical for marketing a new product, and it may cover a wide range of information depending on the intended product and its potential consumers. Fortunately, there is an abundant amount of market information about different product categories. However, the task of gathering and analyzing the information can be overwhelming, particularly when comparative analysis between markets of similar products is required. Examples of common information about product market are as follows:

- What is the current market size of this category of product?
- Is there a predictable market growth over the next few years (normally 2–4 years)?
- What are the driving forces, constraints, and opportunities of the potential product market?
- Would the new product be in the leading segment of the potential market?
- Would the product be sold online or via physical retail distribution?
- What is the extent of market competitiveness domestically and globally?
- What are the market regulations associated with the new product?

Again, these are only examples of information that should be gathered about the market of the intended product. Market information is often represented in data forms that must be carefully analyzed to address the specific questions associated with a certain product. Relying merely on sales personnel to obtain this information may not yield answers to all the key questions pertaining to the intended product. Therefore, it will be important to have marketing personnel of high qualification in the product development team.

3.4.4 Merits and justification

The information-gathering phase should be considered as the most critical phase in the product development cycle as it will set the stage for the process of evaluating the merits of the intended product and determining whether the continuation of developing the product is justifiable. Typically, upon gathering enough information and addressing key questions about the intended product, different members of the product development team should come together and conduct many brainstorming sessions in which each member will have his/her inputs and thoughts about the intended product.

The conclusion of these brainstorming sessions should be stated in the answers of four key questions:

- Is the product idea sound? Is it justifiable?
- Are there merits of the new proposed product that warrant proceeding further with the product development project?
- Should different directions be taken?
- Should the project be terminated?

Answers to these questions should be associated with a clear statement of the merits and an estimated probability of product success leading to either a "Go" or "No-Go" decision by top executives. A "No-Go" choice could mean a complete termination of the product development cycle or giving the idea another chance by repeating the previous phases through gathering more information and conducting new evaluation. It is important to point out that if a product idea is discarded, all relevant information should be archived, as it may lead to other ideas in the future. Indeed, some product ideas that were generated and terminated in some companies have led to innovative products developed by other companies. For example, the principle of air-jet spinning was created at DuPont company, but it was developed later into the well-known air-spinning technology by other companies including the Japanese Murata company and the Swiss Rieter company.

3.4.5 Design analysis

The core of any product development project is product design. This is the process of transforming a product idea into a product model of optimum performance. A typical design analysis begins with design conceptualization, which is the process of generating ideas for an optimum solution to the design problem in view of the anticipated functions of the product. Design conceptualization is a critical phase of design analysis since it deals with the design problem at a macro level through exploring all solution ideas and evaluating the effectiveness of the selected few. This will result in an engineering definition of the design problem. Typically, design analysis is performed via solutions of a series of discrete problems to reach an optimum or semioptimum solution. An optimum solution to a design problem may entail many criteria that will be discussed later in Chapters 4 and 5. A balance between function performance and manufacturing cost must be taken into consideration as this will ultimately determine the competitive value of any product in the marketplace.

The outcome of the design analysis is typically represented by a prototype product, which must be tested, validated, finalized, and presented to the manufacturer for consideration of mass production. A great deal of communication and coordination should be carried out between design engineers and manufacturing technologists to finalize the design process and reach compromising solutions. Specific issues such as raw material specifications, detailed configuration and specifications of the product, assembly planning, manufacturing cost, inherent quality issues, and manufacturing specifications should be addressed.

Today's design analysis is supported by numerous tools that make the analysis more accurate and highly efficient [23–25]. The era of drafting board has largely gone, and now, engineers can use many advanced tools. Few years ago, "2D computer-aided" design was an advanced tool. Now, "3D computer-aided" design has reshaped the entire design process since it enables engineers and designers to see geometrical "volumes," while offering higher flexibility with several design methodologies. 3D printing is another revolutionary development that can be used to build product models or even manufacture the final product. These tools come in a time where engineers are under immense pressure to reduce costs and withstand the higher time-to-market pressure. For the design of textile products, many design tools are used including interactive design programs (e.g., MATLAB GUI) and design apps that makes it possible for independent designers to create custom prints and pattern design for special collections.

Given the fact that we are living in an era where products become obsolete before they depreciate, engineers should utilize product life-cycle management (PLM) strategy [26,27], in which manufacturing data are included in integrated design concepts. Using PLM strategy combined with 3D design tools allows continuous customization of the product design and provides ways to reduce the manufacturing cost of a product.

The selection of raw material is a key element in any design analysis as it directly affects the performance and the cost of manufacturing. A choice of material not approved by procurement may halt the design process, and it may be disapproved by market personnel due to potential high price of the developed product. This is particularly true in today's global market in which raw material may be imported at high prices, particularly raw material of natural resources. In the market environment, this is called avoiding an overall cost of goods sold (COGS). New tools are now introduced to assist engineers in selecting raw material at optimum costs under the general name "purchineering," a symbiosis of standardized purchase processes and the application of preferred components or raw materials by the engineering team.

3.4.6 Mass manufacturing

A product is introduced to the market through mass manufacturing. The transition from a product model to a full manufacturing process often represents a challenge that must be accounted for in the product development cycle. Market personnel can demand low cost and high quality, and engineers can demand optimum functional performance of products, but all these requirements cannot be achieved without good manufacturing performance. Therefore, manufacturing personnel of high qualification should represent an essential member in the product development team. Just as a product can be optimized through design conceptualization and design analysis to reach best performance, manufacturing can as well be conceptualized and designed [28,29].

Different manufacturing methods can be used depending on the product type and production logistics. In general, manufacturing methods can be classified into four main types [30,31]: (a) continuous process, (b) discrete process, (c) job shop, and

(d) batch process. In the textile industry, the conversion of fibers into yarns and fabrics is achieved through a continuous and repetitive manufacturing process characterized by forward successive processing, unchanged machine settings over a long period of time, and a steady flow of material from one stage of processing to the next. In some segments of the industry, discrete manufacturing is also implemented. Examples of discrete manufacturing include the following: the blending of strands (slivers) of natural fibers with strands of synthetic fibers that are manufactured in two different operations and the assembling of yarns of different colors prepared in separate operations (e.g., rope beaming in denim manufacturing). In the fashion industry, manufacturing involves a combination of continuous and discrete processes depending on the type of product and extent of using other accessories in the process.

In today's global market, manufacturing of products is largely impacted by production logistics, and what has traditionally been known as continuous manufacturing is now being implemented in a very discrete fashion by virtue of the use of different manufacturing locations that are far apart from one another. If you are buying a T-shirt from a big retail store in Europe or in the United States today, you should realize that this shirt is a product of a very long journey that may have begun as a pound of cotton produced in the cotton field in Texas, the United States, which had traveled over 7000 miles to Shandong, China, to be spun into a yarn and made into a fabric, which was then shipped another 1800 miles to Southern Asia in Dhaka, Bangladesh, to be made into a finished T-shirt, which was then delivered to a distribution center in Europe or back in the United States before it was finally delivered to the retail store. This long journey is a result of the different labor costs in these countries and the need to minimize manufacturing cost. By comparison with an integrated manufacturing operation using a vertical operation located in one site and in one country, the industry will realize that the few cents per pound saved from manufacturing outsourcing comes at the expense of key criteria of product development including quality consistency and speed of delivery. Furthermore, the distribution of labor cost around the world has been progressively shrinking in recent years and is likely to shrink further in the near future. In 2012, the MIT Forum for Supply Chain Innovation and the publication Supply Chain Digest conducted a joint survey of 340 of their members. The survey found that one-third of American companies with manufacturing overseas said they were considering moving some production to the United States, and about 15% of the respondents said they had already decided to do so.

The "job-shop" model is uniquely different from the discrete model as it does not involve traditional production lines; instead, it is based on production areas. Each area is specialized in manufacturing certain product categories or subcategories. In this regard, production areas may be working in isolation or in some coordinated fashion depending on the product type. A job-shop model may also be converted to a continuous or a discrete model because of high growth of the developed product.

The batch model was originated by IBM in the days when punched cards contained the directions for a computer to follow when running one or more programs. Multiple card decks representing multiple jobs would often be stacked on top of one another in the hopper of a card reader and be run in batches. This model is used in mass manufacturing when continuity in manufacturing is hindered by delay time because

of preparing raw materials or intermediate products. Some weaving processes are considered as batch processes due to the preparation of special yarn beams via mechanical and chemical treatments prior to weaving.

Manufacturing models are also described in other terms such as "lean manufacturing" and "modular manufacturing." Lean manufacturing is a Japanese post-World War II concept that aims at producing value-added products through implementing high efficiency techniques at minimum waste. The problem with implementing lean manufacturing in the traditional textile industry is twofold: an inevitable discontinuity in the manufacturing line for material preparation and inevitable waste, particularly when natural fibers are used.

Modular manufacturing is another concept claimed by the Japanese industry in the early 1980s. It is implemented by segmenting product components into discrete parts, and then, manufacturing each part separately before different parts is assembled in a final product. In principle, modular manufacturing has been implemented partly and at lower efficiency in the traditional textile industry for many years. For example, in the weaving process, warp beams are prepared via winding, sizing, and warp beaming, and filling yarns are prepared separately; then, the two components are interlaced to form a woven fabric. Some companies may even purchase the warp and the filling yarns from two different manufacturers. The benefit of this approach is to encounter no delay in assembling the end product leading to high efficiency. In addition, it involves more focus and skill use of each component of the product. In the Japanese version of modular manufacturing, quality is designed into the product and not inspected into it. In addition, the modular system works on the principle of pull-type production systems, in which the job order comes from the last step to previous steps, leading to a significant reduction in the amount of work needed and a significant optimization of inventory.

Lean and modular manufacturing concepts have been used with various success rates in the fashion industry [30,31], particularly when the goal is to reduce waste, increase efficiency, and focus on labor training. The success of these approaches can be determined by both productivity and quality. However, reaching the desired levels of productivity and quality with these concepts require a readily supportive technology and a great deal of training and motivational efforts of all involved workers. Following the Japanese teamwork style, a team performing modular garment manufacturing will usually receive a piece rate for the entire garment as opposed to a piece rate for each operation. Since rewards are shared equally, each worker must work closely with other workers to produce the end product including unbundling and bundling the stack of garments when it arrives and leaves the workstation, a process that can take up to 5% of the standard sewing time.

Another key aspect of mass manufacturing is quality assurance or minimization of potential quality problems [29]. The importance of this aspect is that no matter how perfect a product may seem, it will be inevitably associated with one or more potential defect that may typically appear during the use of the product. From a consumer's viewpoint, a product's defect is not measured by its magnitude, but rather by its existence, no matter how small or unnoticeable it is. Typically, potential defects should be discovered in the prototype stage and ways to avoid them can be established either in the design analysis or in the manufacturing phase. In case of textile products, there are

two main types of quality problems: inherent problems and induced problems. Inherent problems are typically design related. For example, the selection of highly variable raw material can result in inherent defects or quality problems (shade variation, weak points, thick and thin places, etc.). Obviously, appropriate manufacturing methods can reduce raw material variability (e.g., mixing, blending, and doubling). However, these technological methods are often limited to certain thresholds of variability. Induced problems are typically due to gross manufacturing errors. These types of quality problems should be carefully evaluated in the product development process as it can result in high manufacturing cost. In addition, ways to design a manufacturing system, which is robust against these problems, should be addressed. In all situations, methods of testing materials and end products should be established, and ways to diagnose defects should be identified [29].

3.4.7 Marketing

A product may not fully reach its entire potential consumers without a well-planned marketing strategy. The marketing phase of product development reflects the extent of success of all preceding phases [32,33]. For this reason, marketing experts should represent critical members of the product development team. In many product development processes, marketing experts are confused with consumer experts because of the strong interrelationship between the two and the inevitable overlap of their functions. In this regard, it is important to refer to the key questions listed earlier pertaining to consumer information and market information. It is also important to emphasize the fact that a certain product may attract over 90% of its potential consumers, yet it can only be purchased by less than 30% of those consumers. It is this gap between consumer's interest of a certain product and consumer's willingness to buy that separates marketing aspects from consumer aspects. The lack of willingness to purchase a product could be a direct result of a retail price, which is either higher than the affordability level of a certain cluster of consumers or much higher than product perceived value. These two factors are primarily market related, and they must be evaluated throughout the product development cycle. Neglecting these factors could have many adverse consequences including the following: (1) an immediate consumer's disinterest, leading to what we describe as "consumer's waiting game for price drop, CWGPD"; (2) the entrance of similar products at substantially lower prices, possibly, and "product parity"; and (3) restriction of product marketing to certain markets, or "limited market opportunities (LMOs)."

In view of the previous factors, the marketing strategy of product development should be based on consideration of four key aspects: (1) market segmentation, (2) mass customization, (3) competitive analysis, and (4) product's life cycle. These aspects are discussed in the following sections.

3.4.7.1 Market segmentation analysis

Unlike the traditional marketing approach of "one size fits all," market segmentation analysis (MSA) aims at determining potential market segments that are likely to exhibit a great interest in the new product. Because of the dynamics

of today's market and the rapidly changing consumer's interest, market segments can be created, shifted, moved, or even extinct. Therefore, there is no standard method by which a company can perform MSA. Many approaches can be taken for market segmentation depending on the type of product developed and potential consumers. For traditional textiles and fashion products, different types of market segments may include the following: (1) macro versus micro segments, (2) brick and mortar versus online market segments, and (3) demographic market segments.

Macro versus micro markets

A key segmentation aspect is to divide market segments into two main categories: macro markets and micro markets (see Fig. 3.3). Macro markets are typically represented by potential consumers in large markets such as in a certain continent or a country. In this case, marketing experts must be aware of trade regulations (e.g., tariffs, taxation, and inspection), and product requirements (e.g., performance, safety, and sustainability). Micro markets are represented by consumer clusters within a certain macro market. In this case, marketing experts should be fully aware of many information related to consumer behavior of these clusters such as cultures, religions, social structure, and economical status.

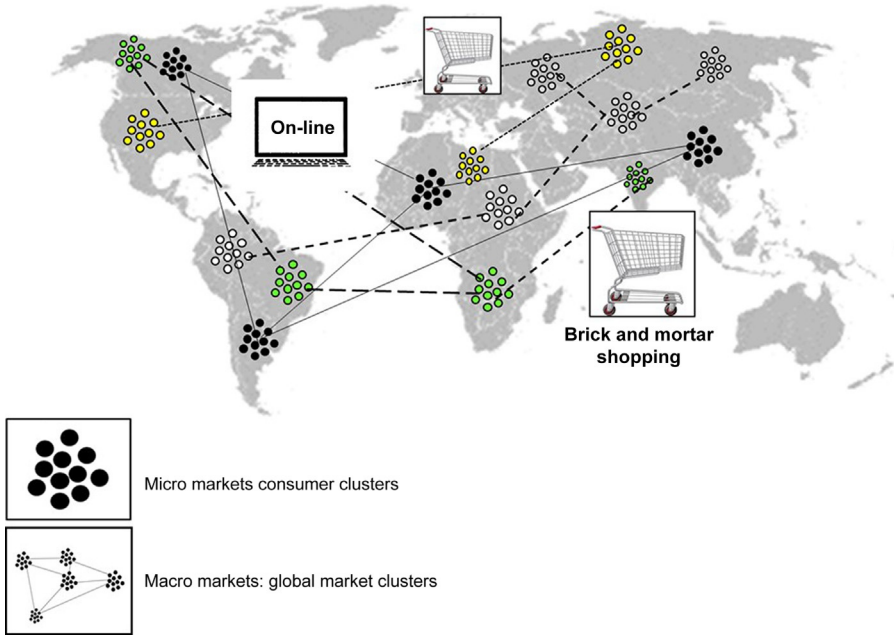


Fig. 3.3 Macro and micro marketing.

Brick and mortar versus online markets

Another important segmentation aspect is to divide market segments by the two main methods of shopping: brick and mortar and online shopping. It is true that online shopping has been growing exponentially in some countries around the world. However, it will perhaps take until the middle of the 21st century to reach a point of equal share between online shopping and brick and mortar shopping universally. This delay is not only due to the slow-to-steady growth in computer and information technology in some countries around the world but also, perhaps, more seriously, due to the lack of supportive infrastructure in many rural areas around the world. According to 2014 United Nation reports (http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html), about 54% of the world's population lives in urban areas, a proportion that is expected to increase to 66% by 2050. Other United Nation reports projected that urbanization combined with the overall growth of the world's population could add another 2.5 billion people to urban populations by 2050, with close to 90% of the increase concentrated in Asia and Africa. In the US market, revenues generated with online apparel and accessories retail sales have increased by more than 25% over a period of 3 years, 2016–18. It was 72.13 billion US dollars in 2016 and over 92 billion US dollars in 2018, and it is expected to soar to a record high of over 120 billion US dollars before 2022 (https://www.statista.com/statistics/278890/us-apparel-and-accessories-retail-e-commerce-revenue/).

Market segmentation by demographic factors

Demographic factors have always been critical for marketing textile and fashion products. These factors are often observed in small clothing retailers that target certain gender or age groups. Indeed, in a visit to a large mall, one will see stores just for women and other just for men, some for casual clothing and other for business attire. Some retailers may be specialized in clothing targeting teenage girls and other targeting teenage boys. Consumers in this age group tend to be brand driven, and they change fashions at a faster rate than adult consumers, particularly in common products such as jeans, blouses, skirts, and shirts. Children clothing retail stores are also common, and the fashion industry has been very creative in this market. Other market opportunities may be in the more specialized stores such as stores for sportswear, hunting, and uniforms.

Marketing products for certain demographic group can be very risky because of the need to excite the group's interest through frequent changes in product style and design. Many products designed for target demographics exhibit short life cycles. Therefore, marketing strategies for these segments should be based on the concept that to build a solid relationship with your consumers, you must identify your typical customer and tailor your marketing pitch accordingly.

3.4.7.2 Mass customization

As indicated previously, market segmentation implies focusing on target consumers to create more direct market opportunities. As this focus transforms from macro segments to micro segments, it becomes necessary to meet every consumer's request

within the target market segment. Since consumer wants and needs will inevitably grow increasingly diverse, satisfying all consumers becomes one of the biggest marketing burdens. This burden has led to the introduction of the concept of mass customization, credited to Stan Davis, who coined the term in his 1987 book *Future Perfect* [34]. Mass customization is generally defined as the production of customized or personalized goods to meet consumer's diverse and changing needs at near mass production lower prices. The idea is seemingly great, and it perhaps represents the ultimate marketing goal of any company. However, achieving mass customization is not a trivial task, and it can be extremely costly.

In general, the concept of mass customization does not offer a magic stick to the industry by which it can meet every consumer's need at near mass production prices. Instead, it provides the industry with a number of tools that can facilitate reaching this ultimate goal including the following [34–36]: information-based supply chain (computers and Internet), product modularization (or working with different segments in the supply chain to deliver products in a shorter time frame), and lean manufacturing (or doing more with less by a continuing effort to eliminate or reduce waste, efficient production design, and logistic-based product distribution). Utilization of these different tools requires high qualifications and extensive training of all workers. In addition, mass customization must be driven by consumer needs before internal design, and only the kind of optimization the consumer would value should be implemented to reduce cost.

Another important point related to mass customization is that satisfying each consumer does not mean satisfying each individual person. As Joseph Pine indicated in his Harvard Business Review article [36], "companies must recognize that every consumer represents multiple markets since consumers want different offerings at different times under different circumstances." This means that marketing analysts should perform cluster analysis to determine common needs among consumer clusters.

3.4.7.3 Competitive analysis

Product developers should be aware of the competitive status of their organizations. If an organization is leading in the competitive race, the pressure imposed on the product development process will be to maintain or improve the organization image and reputation through developing products that are superior to the existing ones or totally innovative. This pressure is typically met by financial and human resources that only leading organizations typically allocate to create and develop new product ideas. Organizations trailing in the competitive race typically face a different type of pressure, which is gaining or regaining consumer confidence in their products, and intense "time-to-market" pressure of new products that can assist them in catching up with leading organizations. This pressure may be further complicated by other factors such as feasibility, risk, and limited resources. New organizations that wish to enter the competitive race should have completely different approaches of product development depending on the size of investment and the organization experience. For new comers with moderate investment, niche markets and specialty products may represent the best options.

As engineers often like to discuss matters using some modeling techniques, it will be beneficial to discuss the different competition models that are likely to exist in the marketplace. Commonly, two main competition models can exist in the market [37–41]: pure competition and monopolistic competition. Pure competition is a market scenario in which many autonomous and knowledgeable suppliers and buyers of an identical product are present, yet none of which are capable of gaining price advantage or changing the price. Typical conditions of a pure competition model are as follows:

1. No single supplier or buyer is large enough or powerful enough to affect the price of the product.
2. Products are identical, and they exhibit no disparity in quality, and no brand name or image issues exist. As a result, customers are less likely to prefer one supplier over another.
3. No collusion (conspiracy or hidden agreements). As a result, each supplier and buyer will act autonomously. This means suppliers would compete against one another for the consumer's dollar. Buyers would also compete against each other and against the supplier to obtain the best price.
4. No mutual loyalty is necessary between the buyers and the suppliers as all products are identical giving little reason for loyalty to a supplier on the basis of product merits.
5. Nonregulated market environment. This means that suppliers and buyers are free to get into, conduct, and get out of business. This makes it difficult for a single supplier to dominate the market and dictate unfavorable prices as other suppliers can freely enter the market and stabilize the price.

In today's globally competitive market, pure competition hardly exists, and the more common competition model is the so-called monopolistic competition. This model typically exists at any time the conditions of pure competition listed previously are not met. Under a monopolistic competition model, products cannot be considered as identical even if they are seemingly perceived to be the same. As a result, product developers must continually strive to establish features in their products that are uniquely different from those of competitor products. This may require design emphasis on performance and performance/quality differentiation rather than price differentiation.

Monopolistic competition may be represented by many familiar models in the market place. These include the following: oligopoly, pure monopoly, and near monopoly. Oligopoly implies a market of few large firms that dominate the market and have the ability to influence prices. These firms tend to have common strategies, and one may follow another in product lines, price change, or customer service procedures. They also tend to keep their prices and their product values far from reaching by smaller competitors. Despite their independent management, they always seem to act in unity particularly in price fixing and in dividing the market so that each is guaranteed to sell a certain quantity. Familiar organizations that operate largely under oligopoly model include Coca Cola and Pepsi Cola and some giant airlines.

Pure monopoly is a model, which hardly exists in the real world as it implies domination by one organization of a specific product that has no substitutes. Even if this model holds for some time, other competitors will certainly come into play and attempt to develop similar or better products. A more realistic model is the

so-called near monopoly. This is best illustrated by its derivatives such as natural monopoly, government monopoly, geographic monopoly, and technological monopoly. Natural monopoly is when society is best served by the existence of monopoly. Organizations that enjoy natural monopoly are typically subjected to many regulations to serve the interest of the consumer. As they grow larger, they are likely to bring about lower prices because of lower costs (the economy of scale). Government monopoly is a common condition in all countries, but mostly in the third world countries. Under this condition, the government owns, operates, and develops products for the public. These are mostly of service nature such as healthcare, public transportation, and utility. Geographic monopoly is a historical type of near monopoly that some organizations have enjoyed as a result of their geographic locations and consumer demands in these locations. With the increasing trend toward global competitive market, this type of monopoly is likely to decline as many organizations will find their ways through different cultures and different areas in the world. Technological monopoly is perhaps the most accepted type of near monopoly and the most difficult one to compete against. From an engineering perspective, technological monopoly lies in the heart of product development. It reflects the special rights that an organization can enjoy for developing new products. In most countries including the United States, these organizations are given exclusive rights to manufacture, use, or sell new products that were invented by them.

In light of the previous discussion, it is critical that competitive analysis should be a part of the product development process. Unfortunately, there is no universal approach for performing competitive analysis at the product development stage. As a result, different organizations seek different approaches to determine their competitive status. Some organizations rely on their market share statistics to determine their competitive status. Historically, this approach has been useful in creating organizational confidence and investors' trust. However, at the product development stage, more intimate knowledge of the competitive status of an organization in view of the products being developed can be critical.

In a competitive environment in which monopolistic competition models are likely to prevail, an organization should always be aware of the external forces influencing the market. These can be represented by a competitive loop showing the various market forces, which can serve as a guideline for possible actions toward achieving competitive advantages [4,5,29]. A simple competitive loop will consist of several organizations competing for the same consumer or potential buyer. In this environment, each organization attempts to attract the consumer to its product through offering better function performance, lower price, better quality, and more reliable service than the other organizations. This type of competitive loops (Fig. 3.4) represents a simple case of competition that is normally experienced in domestic markets.

In a globally competitive market, an organization is typically subject to many market forces some of which can have significant impacts on the progress of product development and the competitive status of the organization. In addition to local competitors, the organization may be subject to foreign competitors. This imposes additional market challenges such as cultural gaps, coordination, logistics, and communication issues. Trade, standards, and consumer organizations will also play

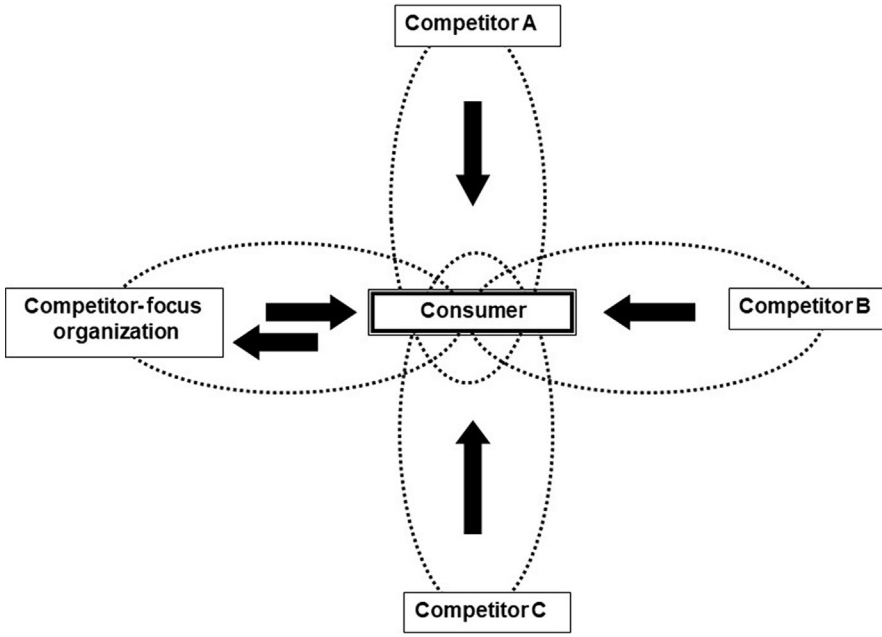


Fig. 3.4 Simple competitive loop.

a larger role in the global market. These organizations are likely to coordinate their efforts to achieve fair trade, standardized measures, common product specifications, and more knowledgeable consumers. These various forces are illustrated in the competitive loop shown in Fig. 3.5.

3.4.7.4 Product life cycle

In the previous sections, the term "life cycle" was used repeatedly to describe the progressive performance of a product in the marketplace. Product life-cycle analysis has become an essential task of product development in today's global market. In general, a product life cycle consists of four common phases of product performance [27,29,42,43]: initiation, growth, maturity, and decline. A generalized product performance profile over a complete life cycle is shown in Fig. 3.6. Common market changes associated with product life cycle are demonstrated in Fig. 3.7. Although some features of each stage of a product life cycle may vary depending on the product type, most products will exhibit common features such as those described in Table 3.1.

The initiation stage of a product life cycle encompasses the generation of product idea and the different tasks of product development discussed earlier. Toward the end of this stage, a product undergoes rapid changes and adjustment to optimize its performance in the marketplace. In some situations, the product undergoes extensive testing by selected customers or potential users of the product. A user testing of a product not only reveals the extent of success of the design process but also evaluates the

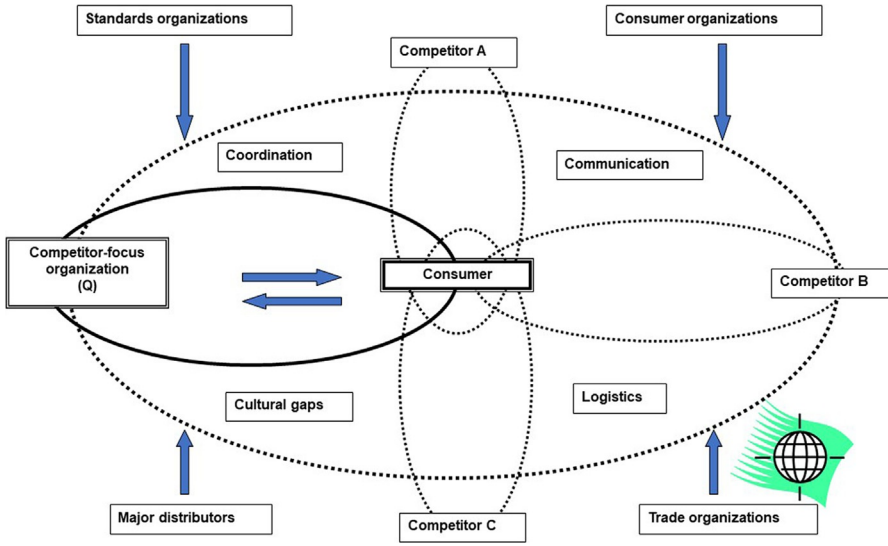


Fig. 3.5 Complex competitive loop.

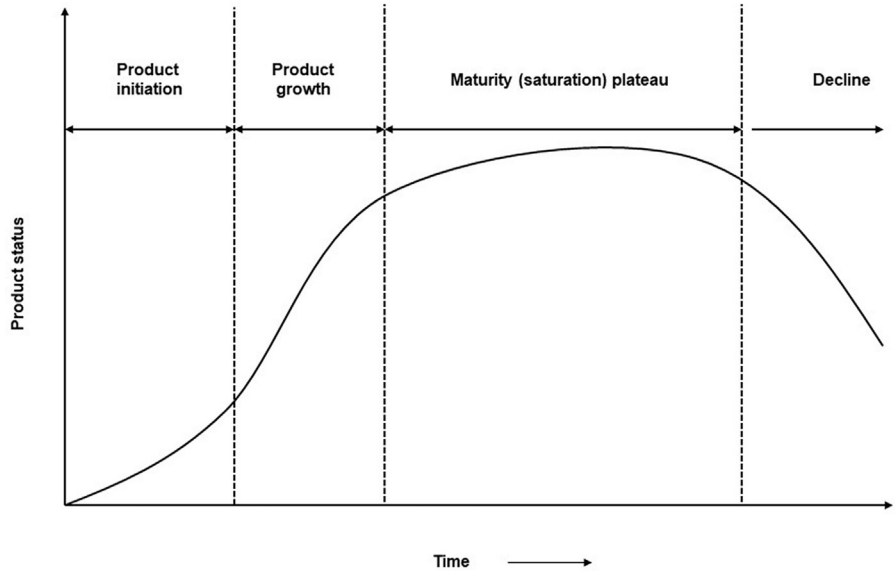


Fig. 3.6 Basic stages of product life cycle.

outcome of the assembly process of the product during manufacturing. More importantly, product testing by potential users may also reveal other concerns or interests that have been overlooked during the design or the manufacturing process. When intense "time-to-market" pressure increases, some organizations rush into introducing

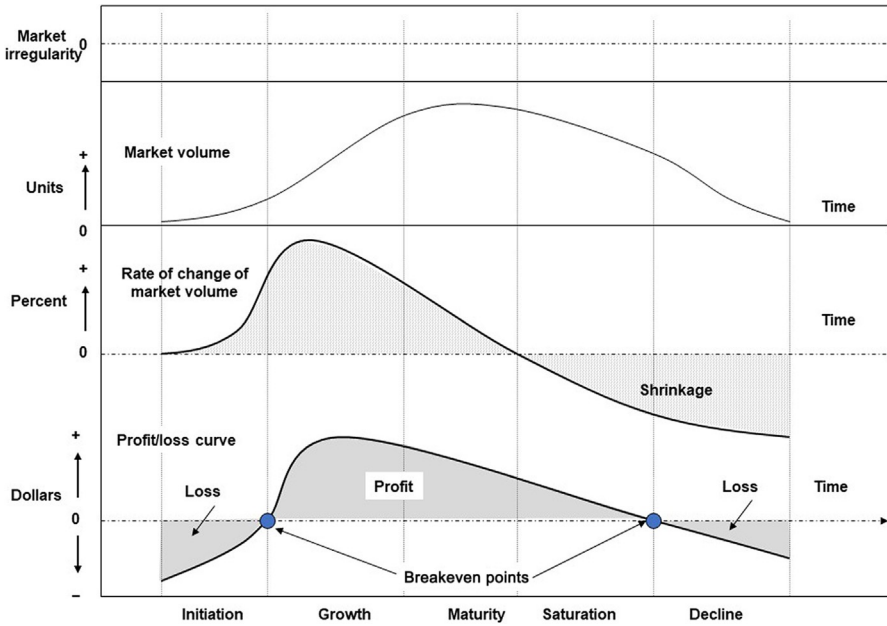


Fig. 3.7 Market evolution pattern: market life cycle.

their new products without extensive user testing. As a result, many new products may be recalled shortly after their introduction to the market for safety and liability reasons or due to some functional flaws.

From a market viewpoint, the initiation stage of a product life cycle is typically associated with erratic patterns of growth and instability in the market. This a direct result of the slow customer's awareness of the product at the initiation stage, particularly when promotion of the new product is limited due to cost reasons. Market volume typically expands slowly during this period because of high market resistance. The rate of growth increases faster than the market volume itself, because each additional dollar represents a higher growth percentage than at any later stage of the cycle. Assuming that the company initiating the market is a pioneer and recognizing that the initial outlay for product and market development is often quite substantial, the product initiation stage is generally characterized by cost exceeding revenues (or net loss). As a company approaches the end of this phase, it should reach a breakeven point on innovation. This means that its total revenue should at least be equal to its total cost. From a competitive viewpoint, if two companies share the pioneering stage of a certain product, the company that reaches the breakeven point first will likely have more flexibility and competitive advantage in the next stage of the product life cycle.

Passing the initiation stage is critical for any product as failure to achieve that can only mean substantial losses to the organization developing the product. The period of an initiation stage can take will vary depending on many factors

Table 3.1 Product and market attributes associated with the product life cycle [29].

Life-cycle phase	Product evolutionary attributes	Market evolutionary attributes
Initiation	– Invention to innovation – Rapid changes and adjustment to optimize product performance – Possible instability in technology	– Customer or consumer awareness and acceptance of the product is slow – Erratic pattern of growth in market structure and competitive status – Market volume typically expands slowly because of potential market resistance – Possible initial net loss because of costs exceeding revenues
Growth	– Better knowledge of product capabilities and flaws – Further attempts to reduce manufacturing cost as mass production continues – More customization of product performance to meet customer requirements	– Customer awareness increases rapidly during this period until it reaches a maximum at the end of the growth period – Steady or rapid increase in market volume – Revenues exceed cost (net gain)
Maturity to saturation	– Product development largely ceases – New ideas may be introduced to redesign, rejuvenate the product, or introduce better products	– Wide acceptance of the product – Customer expectation of lower price as sales volume increases – Slow rate of market volume
Decline	– Production rate and volume decline rapidly – Product support declines rapidly	– Market volume shrinks – Customers shift to other alternatives

including the following: the type of product, resources, time-to-market pressure, competitive pressure, and customer acceptance. Most traditional textile products exhibit short initiation stage. Technical textile products on the other hand are likely to be associated with longer initiation stages by virtue of the design complexity and marketing challenges.

After the initial stage, the product enters the growth stage of the product life cycle. In this stage, the product should exhibit booming sales, and the growth rate should also increase. The profile of Fig. 3.7 shows a peak of growth rate at about the middle of this stage. Further growth occurs at a decreasing rate, often because of steadily expanding base. Although profit reaches its highest during the growth stage, the trend may reverse in the middle of this phase as declining prices and rising costs prevail.

Products that exhibit steady growth are likely to continue their growth, normally at smaller rates to the next phase of product life cycle, which is the maturity stage. In this stage, the market volume continues to grow at a slower rate until it reaches the stagnation level at the end of this stage. Profits diminish but can still be healthy. Markets that have grown to maturity may reach a saturation stage in which volume and profit/loss all go through a negative change rate. Costs and competitive pressure reduce profits further until they cross the breakeven point again at the end of this stage.

Maturity may continue for many years depending on the extent of customer satisfaction with the product (as indicated by a steady market volume) and the willingness of the organization to continue supplying the product. However, it is at this stage and before a product enters the saturation stage that an organization should revisit the product concept and make important decisions such as (a) improving the product model so that a new generation of the product can be initiated, (b) terminating the product concept and turn into another product idea, or (c) prolonging the maturity stage through promotional activities or price reduction.

Product decline is an inevitable stage of the life cycle of virtually any product that must be expected and anticipated by any organization. This is a fact that has been historically realized by many organizations particularly those that produce fashionable textile products. Typically, fashions are associated with short product life cycles as a result of a self-imposed decline so that new fashions associated with higher profits can be introduced. Decline may also occur for other products because of the introduction of new products that exhibit better performance or meet new demands. This will result in shrinkage of market volume because of booming substitute markets.

In the textile industry, one can find numerous examples of products at various stages of their life cycle. For example, the development of high-speed shuttleless looms has rapidly forced conventional shuttle looms into a decline phase. On the spinning side, new yarn-forming technologies such as rotor spinning, air-jet spinning and friction spinning with their superior production rates have largely slowed the growth of the conventional ring spinning. However, they could not fully eliminate ring spinning in niche markets such as fine-woven fabrics and soft knit goods. Products such as cloth diapers have suffered major decline because of the development of disposable diapers. Now, there are new trends toward the use of cloth diapers again because of environmental concerns and adverse effects including the outbreak of diaper rash and skin irritation.

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Key aspects of design conceptualization

4

4.1 Introduction

In Chapter 3, basic concepts and tasks of product development were introduced. It was clearly indicated that product design is the core task of a product development cycle. It is through design that a problem is solved, and a product prototype is constructed. If this task is not achieved, nothing else matters in the product development process. Product design is primarily an engineering job. Indeed, the term design is often considered synonymous to the term engineering. To realize the critical importance of design in the world of engineering, it will be useful to refer to the concept of "Engineering Operating System, EOS" [1]. In this concept, it was demonstrated that engineering design represents the vehicle that transform science to technology (see Fig. 4.1). Engineers use science to convert idealized concepts into real product or process models. Technology can then take these models and convert them into physical products or actual processes. This simple fact is often masked by the inevitable nonlinearity in the conversion of ideas into products or processes.

Ideas may stem from human creative thinking, but an idea that has no scientific basis or supported by scientific evidences will likely end up as merely an idea without true merits. On the other hand, many ideas that were based on true science have never been materialized into physical products; they are still awaiting engineering design to convert them into economic feasibility and realistic products. Science sets the basis or the foundation for engineers to work, but science alone does not design products only explores possibilities. Some ideas take many years before they are developed into familiar products. For example, ancient Egyptians used some forms of chew sticks, which were a thin twig with a frayed end, to brush their teeth. Those were hygienically appropriate since they were made from natural plants and they helped avoiding teeth gum inflammation caused by bacterial accumulation. This was the science of the old days, which led to the design of the toothbrush as we know it today. Many people do not know that the first product made from nylon after its discovery in 1935 was the DuPont tooth brush in 1938. This was a classic case of science turning into technology via engineering design. Indeed, the first nylon toothbrush was called Doctor West's Miracle Toothbrush.

The cyclical pattern of science, engineering, and technology stems from the fact that these three branches of human knowledge must interact on regular basis. Engineering will always design to convert science into product models; technology will always use design outcomes to produce physical products. However, feedback is critical for science, engineering, and technology to operate. Science is developed through exploring real models developed by engineers, and engineers improve their designs through technological feedbacks, and technology may bypass engineering

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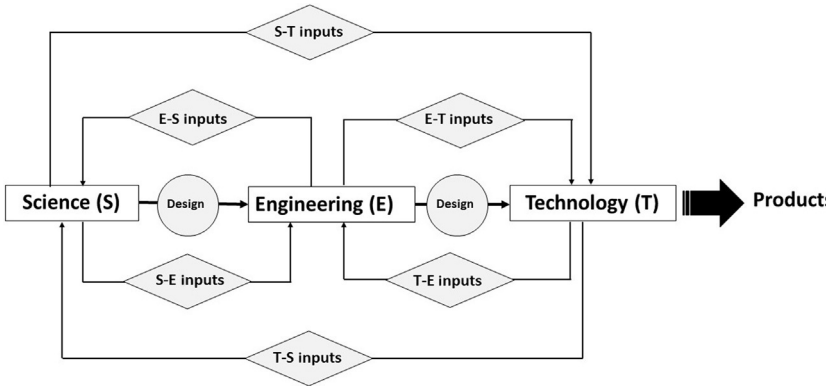


Fig. 4.1 Engineering operating system (EOS): bridging science, engineering, and technology.

design by learning from science how to fine-tune or make some adjustments to achieve a desired performance. The operating system for these interactions is engineering design.

4.2 Definition of engineering design

The Accreditation Board for Engineering and Technology (ABET) in its 2015–16 report titled Criteria for Accrediting Engineering programs (https://www.abet.org/) defines engineering design as "the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs." ABET also indicates that among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.

The earlier definition is adopted by virtually all engineering programs in the United States irrespective of the engineering education discipline. It does not reflect a typical design process, but rather point out some of the key elements of design that are commonly considered. On the other hand, it leaves many design aspects open for interpretation. For example, the term "desired needs" in this definition does not imply if these needs stem from a designer's viewpoint or a user's viewpoint, which may be completely different things. The use of the term "decision-making" may also be somewhat confusing since it does not apply to the approval of a product model being designed by the product developer, which is the key decision, but rather to the acceptance of a model by the engineers who developed it.

Perhaps, the most critical term missing in the ABET definition are "problem-solving" and "uncertainty." A typical engineer spends most of his/her time concerned with problems and their potential solutions. Because engineers often create incredible things, many people outside the field think that engineers normally think big; it is often the opposite. As Elon Musk, the world leading entrepreneur of electric cars

said: "I don't spend my time pontificating about high-concept things; I spend my time solving engineering and manufacturing problems." Buckminster Fuller, another American architect and engineer, said: "When I am working on a problem, I never think about beauty but when I have finished, if the solution is not beautiful, I know it is wrong." Freeman Dyson, an English-born American theoretical physicist and mathematician known for his work in quantum electrodynamics, said: "A good engineer is a person who makes a design that works with as few ideas as possible. There are no prima donnas in engineering."

Today, engineers work under tremendous pressure to design new products or improve the design of existing products with the potential of failure far exceeding the potential for success as discussed in Chapter 3. Failure can only come from trying, which means uncertainty. A fear of failure will hinder the iterative process, which is the essence of engineering design. Most successful engineers see failure as a recipe for success. Henry Petroski, an American engineer specializing in failure analysis, said: "Successful engineering is all about understanding how things break or fail." The search for an optimum solution through the iterative process of a design cycle is often associated with solutions transformed into product models that turn out to be functionally disastrous. Even when an optimum solution is reached from an engineering's perspective, transforming a product prototype into a physical product can be associated with failure resulting from operating factors that have not been considered in the design analysis. Under the time-to-market pressure, design engineers often work within a limited timeframe and with limited resources, which may increase the potential of failure. Nevertheless, most engineers understand that it is better to fail early or fail now than designing a product that will encounter failure upon usage or in the hand of the customer. In many situations, building a product model can be very costly, and the design project is terminated due to high cost. This type of failure often results in an intellectual property that can be later transformed into a successful product.

It is the author's opinion that engineering design should be simply defined as an iterative problem-solving process based on science and creative thinking that can provide optimum functional and economical solutions for existing products or create new product models in which these solutions are inherently present with the result being satisfying consumer needs or creating new consumer wants. The term science encompasses all scientific tools derived from mathematics, physics, and chemistry as well as their applications in engineering sciences, and creative thinking implies the ability to design a product that has optimum function performance and attractive aesthetic properties.

4.3 The product design cycle

A typical design project in engineering education begins with a specific problem given to students to solve. For example, "As a textile engineer, what's the best way to increase filtration efficiency or minimize dust accumulation in a textile filter? Or what is the best geotextile pattern to enforce soil structure? Or what is the best

way to produce a light-weight bulletproof vest for law enforcement officers? These are all good problems that are given within the timeframe of a project in which students jump immediately into design analysis. In the real world, a design project involves much wider range of tasks and activities that require planning, conceptualization, design analysis, product prototype, evaluation, and manufacturing planning. These are circular tasks, which can be best illustrated by a design cycle. The use of cycles to illustrate engineering tasks is a common approach, which stems from the need for an iterative procedure to reach compromising solutions of engineering problems. A universal or standard product design cycle cannot be established since a design approach may vary depending on many factors including the following: product type, options, resources, cost, relevant information, and personnel qualification.

A simple example of a design cycle is shown in Fig. 4.2. The foundation of a product design cycle consists of two key aspects [2–5]: design planning and design conceptualization. Design planning implies making basic requirements of a design project available prior to entering a design cycle. These include the following: qualified personnel (e.g., design engineers, manufacturing engineers, and marketing personnel), hardware and software, information sources, and natural resources. The second foundation of a product design cycle is design conceptualization. This is the process of generating ideas for an optimum solution to the design problem. As will be discussed later, design conceptualization is the most critical aspect of design as it determines whether a product idea is justifiable in view of functional merits, costs, and value with the results being to proceed with the design project, modify the product idea, or terminate the project. If the outcome of design conceptualization is to proceed with the design project, the product design cycle is then implemented as shown in Fig. 4.2.

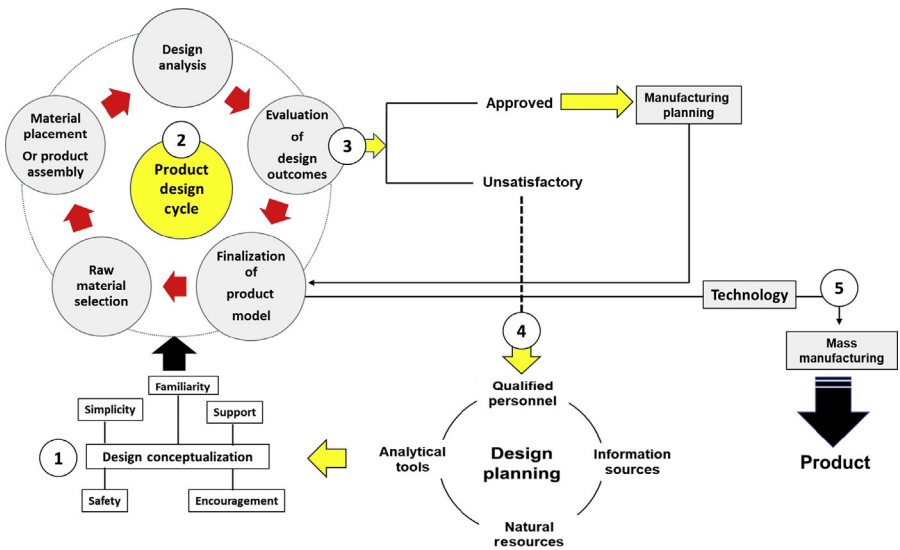


Fig. 4.2 Key tasks of a product design cycle.

The common task sequence of a product design cycle is as follows: raw material selection, material placement or product assembly, design analysis, and evaluation of design outcomes (typically a product prototype or virtual view of a designed product). The task of raw material selection and placement will largely depend on whether the intended product is a modification of an existing one or a totally new product. Typically, the latter will involve a greater effort than the former. In Chapter 7, the subject of raw material selection will be discussed in detail. Material placement or product assembly is first initiated based on previous experience and finalized after performing design analysis. Design analysis is implemented using appropriate analytical and modeling tools to explore the various factors influencing product performance and obtain an optimum solution leading to a product model.

In today's information era, numerous analytical tools are available using powerful software programs specialized in design analysis. A design analysis will yield an initial product model that should be tested and evaluated to determine whether it should be finalized or modified through an iterative analysis in which the design cycle is revisited. The evaluation of an initial product model can be performed either by the original design team or by external experts representing other design engineers, manufacturing engineers, and marketing personnel. If this evaluation reveals an acceptable product model, the design team will then proceed by finalizing the product model. If the results are unsatisfactory, further analysis should be made in which the design cycle is repeated perhaps with consideration of alternative raw materials, different product assemblies, or different design approaches. This cycle may continue until a satisfactory model is developed.

Product design cycles should be carefully implemented in view of the anticipated complexity of the intended product. For simple products (e.g., simple constructions or pre-existing products that require slight modifications), the design cycle will typically be short, and it may be completed in one or two iterative loops at the end of which a product model is finalized and handed to the manufacturing process. Design engineers involved in this type of design are typically given limited time to complete the design project, and they normally have long experience with the nature of the intended product (e.g., strengths and weaknesses, specific alterations, customer complaints, and competitive advantages or disadvantages). For newly developed products, the design cycle can be long, and many loops of the iterative procedure may be required to reach optimum product performance at a minimum cost. In this case, a special design team with more in-depth knowledge of the intended product should be formed. The time allowed to complete the design project should be longer to allow reaching a saturation point of the learning curve. Later in this chapter, this point will be illustrated further using the concept of "resource-time elapse profile".

In all situations, the final product model is communicated with manufacturing engineers to determine the key manufacturing aspects associated with making the product at a large scale. These include the following: manufacturing planning, mass manufacturing, process control, automation, and problem-solving of quality issues. These tasks are performed through continuous coordination between the design team and manufacturing engineers.

4.4 Design conceptualization

Before an engineer jumps into a detailed and often complex design analysis, he/she must pause and think of the big picture first. Questions such as why a product is needed? Is it feasible? Is it cost justifiable? What design features are needed? Does it add value to consumer? Is it a recycle of an old idea or truly innovative? Are tools and materials readily available to perform design? How long it will take to complete a design project? Is success certain? How much it would cost to develop a product prototype? This process is called "design conceptualization," and the answers to these questions should yield a "design concept" associated with the intended product. Design conceptualization practices often result in a great deal of learning and many visionary thoughts. Some concepts may be driven by long experience with similar products, other concepts may be driven by creative thinking, and some concepts may be even a result of intuitive knowledge.

It is the author's opinion that students should be taught design conceptualization before they learn about design analysis. In other words, schools should teach the profession before they hand the tools to the students by focusing first on what and why before reaching the point of how. In a survey made by the author 10 years ago, the participants were all students doing their design senior projects. Key questions of the survey were like those listed earlier. Responses were very disappointing, and they all indicated that students were mainly analysis focused and conceptually poor. Engineering students need to think in abstract mode before going into deep analysis.

Can a successful design be achieved without design conceptualization? Many engineers would argue "yes." Indeed, that is probably what Elon Musk alluded to in his statement "I don't spend my time pontificating about high-concept things; I spend my time solving engineering and manufacturing problems." However, Elon Musk is not an engineer by education; he is a great entrepreneur and a very creative visionary engineering practitioner with a degree in physics and business. He also lost hundreds of millions of dollars in failing projects before he came to his current success in the car business, and even after that, he was demoted by the company he created. The point here is that in the absence of design conceptualization, design can become a risky business with high chance of failure. If you can afford the cost of failure, then you may get by without conceptualization. For this reason, giant companies have adopted new design concepts including design thinking, lean startups, and agile (to be discussed in Chapter 6) for the sole reason of minimizing the cost of design and product development projects.

Key criteria of design conceptualization include the following [3]: simplicity, support, familiarity, encouragement, and safety robustness. These criteria are introduced in the succeeding text.

Simplicity—A key aspect of design is that no matter how complicated the design analysis may be, it should ultimately result in a great simplicity from a product's user viewpoint. This means that the final product model should be associated with a simple and straightforward usability. The importance of this principle is that engineers often focus on the product function and pay minimum attention to the usability aspect.

These are two different attributes of a product that should be addressed in design conceptualization. For example, the function of an *E*-fibrous jacket equipped with some nanomedical sensors is to monitor some body functions such as blood pressure, sweat rate, or heartbeats. Reaching these functions would require a great deal of sophisticated work. However, from a user's viewpoint, easy handling and simple access to the outputs (signals or measures) should be achieved in the design process. This requires a well-organized interface that supports the user's benefits at the highest possible efficiency. In other words, the user should gain the benefits of the product with minimum interactions and minimum interference with the product function.

Support—Sometime, the notion of an engineering sequence of using a product can be different from the sequence that would be naturally followed by a typical user of a product. In this type of situations, it will be important to either adopt the user's sequence to meet the product functions or to clearly guide the user to the appropriate sequence. In other words, the user should be in control of the product, and any design assistance should take the shape of a proactive and not a reactive approach. Design support is often critical in some products as it could mean liability and life threatening. For example, a safe jumping off a helicopter can only be achieved by an easy support design of a parachute to allow easy opening, and an air bag should be immediately deployed without user's input at the time of collision.

Familiarity—One of the key aspects of design conceptualization is to build on users' prior knowledge of a product, which was gained from experience with similar products. The user of a product should not have to learn too many new things to perform familiar tasks. This is particularly true when the product in question is an extension or a modified version of an existing one.

Encouragement—Predictability is a key aspect of design concepts. In other words, a user's interaction with a product should yield expected or predictable outcomes. This principle requires understanding the concept of user's task experience by design engineers, which increase the user's confidence in using and exploring the product capabilities without fear of adverse consequences. The concept of user's task experience is heavily implemented in the design of most software programs in the area of user-computer interface, where a user can always try things even if they are wrong relying on the "undo" button. With physical products, this aspect of design is often difficult to implement, and misuse of products often result in irreversible consequences. In many garment products, guidelines on washing, drying, and maintaining clothes are often presented in product labels. As the industry moves heavily into smart fashions, these guidelines should be self-directed and self-controlled.

Safety robustness—The safety aspect deals not only with the adverse impact that the normal use of a product may cause to the user as a result of safety-hazard design but also with what some unintentional errors or confusions during the use of a product may cause. Again, this could result in product liability issues. Therefore, a product should be designed with safety robustness features against use and abuse of products.

The process of design conceptualization requires a great deal of brainstorming to examine the merits and the feasibility of a product idea in view of physical, economic, and functional factors. For example, if alternative resources to the existing ones impose high cost, design conceptualization will aim at ways to reduce the cost or

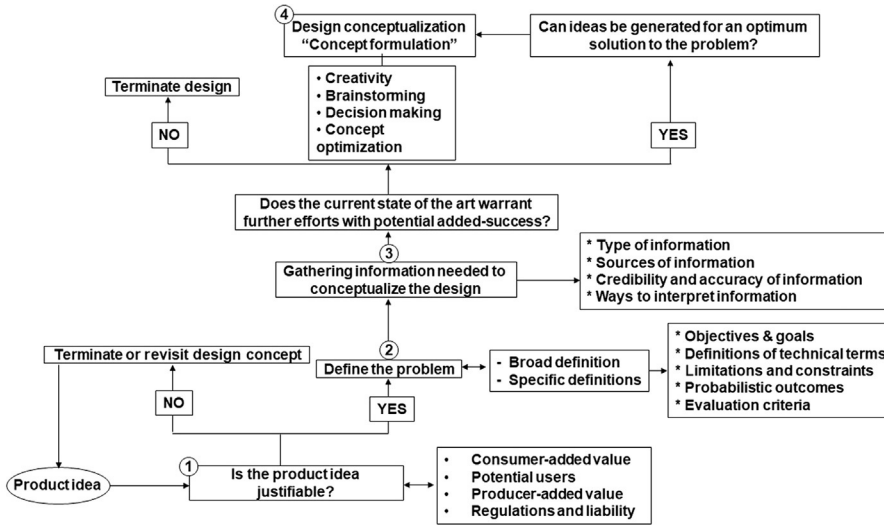


Fig. 4.3 Key steps toward design conceptualization.

to justify the added cost in view of long-term benefits. In this regard, issues such as value, cost, price, and liability should be accounted for in design conceptualization [2, 3]. There is no standard procedure of design conceptualization, but there are many common aspects involved in the process of design conceptualization. These aspects are demonstrated by the simple conceptualization cycle illustrated in Fig. 4.3, and they are discussed in the succeeding text.

4.4.1 Product justification

Some of the key factors determining the justification of a product idea include the following: (a) consumer-added value reflected in the specific needs or wants for a product, (b) potential users or customers of a product (user category, size, income, culture, and location), (c) producer-added value (profit, image, reputation, etc.), and (d) regulations and liability (marketing, safety, and environmental aspects). These factors must be evaluated carefully to justify further efforts toward designing a product.

The consumer-added value of any product should be determined through market research that can reveal either dissatisfaction with a current product or a customer's interest of a new product. Any product idea should be partly justified in view of its potential user. In this regard, the key issue is whether the product represents a common consumer product that will potentially be used by a vast majority of people, or it may be directed toward a specialty application or a market niche. The justification aspect here stems from the fact that depending on the potential user of a product, the cost of developing and supporting a product may vary substantially. In general, different

users may exhibit different qualifications that are reflected in their handling of the product. For common products, the wide range of user qualification may result in a wide range of product handling, from perfect use to misuse or even accidental abuse of the product. This point has typically been overlooked in traditional design philosophies due to the focus of the design process strictly on the specific functions of the product. In today's market, a misuse or accidental abuse of a product by a consumer could be blamed on the product developer, on the ground that an appropriately designed product should be easy to use and should be robust against potential misuse [1].

The producer-added value is reflected in the entitlement of a producer to make profit for the effort made in developing a product. When a product is a consumption-type product used by many consumers, this value is reflected in the economics of scale, which give rise to lower per unit costs due to more specialization of labor and more integrated technology to boost production volumes. This in turn results in higher revenues and more profit. Most traditional textile products belong to this category of products. Highly specialized products (machines, technical textiles, heavy-duty electronics, civil constructions, etc.) are typically associated with market niches and specific customers. Few product units are made, and the high cost of design and manufacturing is justifiable in view of the appreciated value added by customers and the limited number of producers.

Regulations and liability are often considered in product planning or marketing. However, some regulations can have a direct impact on the design concept. Certainly, a product design that does not account for market regulations will not find its way to the market. Different products may be associated with different types of regulations depending on the type of product and its potential users. Most traditional fibrous products are associated with regulations dealing with their maintenance aspects such as washing, drying, and handling. Companies that design clothing for children must be fully aware of the safety precautionary rules that are established to assure safe and appropriate use of this product. For example, the US Consumer Product Safety Commission sets national safety standards for children's sleepwear flammability. These standards are designed to protect children from burn injuries if they come in contact with an open flame, such as a match or stove burner. Under amended federal safety rules, garments sold as children's sleepwear must be flame-resistant or snug-fitting garments. The latter need not be flame resistant because they are made to fit closely against a child's body. Snug-fitting sleepwear does not ignite easily, and even if ignited, it does not burn readily because there is little oxygen to feed fire.

For technical textile products, numerous rules and regulations are established to insure reliability, durability, and safety. These are updated and published regularly by many organizations. For example, fabric requirements for car interior safety are regulated by federal motor vehicle safety standards and regulations established by the US Department of Transportation or the National Highway Traffic Safety Assurance-Office of Vehicle Safety Compliance. Bulletproof vests are regulated by the Justice Department federal safety guidelines Body Armor Safety Initiatives. Protective clothing systems are regulated by many organizations including the Occupational Safety and Health Administration (OSHA) and the Environmental Protection

Agency (EPA). Medical products are divided into broad categories such as hygienic absorbent products, hospital and healthcare products, implants, and scaffolds. Because of their significant impacts on human health and safety, they are produced according to strict regulations and legislations. These should be designed-in and not just considered via product instructions. Sometimes regulations can restrict some potential users from accessing the product for their own safety or for the safety of others. Many medicines, for examples, are only accessed via prescriptions. In case of bulletproof vests, regulations and laws make it unlawful to acquire or to use bulletproof vests by criminals or people that are convicted of a felony (United States Law 18USC931).

The outcome of a product justification process is typically a multiple-choice decision to either continue with the design of a product, terminate the design process, or revisit the design concept. In many situations, the time to reach this decision is shortened by the extent of existing knowledge and the qualification of the engineers developing the design concept. In other situations, justification of a new product idea can be time consuming due to a great deal of uncertainty about potential consumer-added value and producer-added value. This is particularly true in view of the trade-off between time-to-market risk and the likelihood of success.

4.4.2 Define the design problem

Defining a design problem can be a part of the justification phase, particularly when economic feasibility is questioned. However, most engineers feel confident that any problem can be solved if it is appropriately defined. The term "problem" is commonly used to imply a negative situation, caused by some unpredictable, or predictable factors, which requires solution. In engineering design, this term reflects a question raised for inquiry, consideration, or solution. Accordingly, any design project is associated with a problem or perhaps a set of problems that must be solved to reach a product of optimum performance, with "optimum" meaning the amount or degree of something that is most favorable to some end or the greatest degree attained or attainable under implied or specified conditions.

In general, a design process is often viewed as a series of discrete problems that must be solved, one after the other, to reach an optimum or semioptimum solution. Unlike systematic problems that are typically experienced in manufacturing or in handling customer complaints, a design problem is often not "a problem to react to," but rather "a problem to anticipate and attack." In other words, a design problem represents a statement of challenging aspects associated with a proposed product idea.

The key to reaching an optimum solution to a design problem is to clearly and specifically define the problem. In a typical design process, one can divide problem definitions into two main categories: broad definitions and specific definitions. The order of these two categories is not important. A design team may commence with a broad definition of the problem and break it down into more specific definitions of the problem.

On the other hand, a design team with long experience of the product type may begin by establishing specific definitions of many problems associated with the product design then integrate these to form a broader or a collective definition.

A broad definition of a design problem may be initiated by establishing a general description of the proposed product. For example, a bulletproof vest is generally described as an article of protective clothing that works as a form of armor to minimize injury from projectiles fired from handguns, shotguns, and rifles. This broad description serves as a generalized concept of the product that may result in hundreds of product options and alternatives. A specific definition of the product is typically a derivative of the broad definition that deals with more specific aspects. For example, a more specific definition of the design problem of the bulletproof vest would be to specify the level of protection expected; say, against 9-mm full metal jacketed round nose bullets, with nominal masses of 8.0 or 124 g, impacting at a maximum velocity of 427 m/s. This is a performance-related definition. Another specific definition may be stated as "a three-layer garment construction, with protective inserts that exceed the overall fabric weight by no more than 20%, with garment layers being reducible to accommodate less risky situations." This is a structural-related definition.

Under time-to-market intense pressure, the phase of defining a problem is often reduced to one or two problems or strictly applied to few specific performance aspects of the product. As a result, some products find their way to the marketplace with problems that have not been fully defined in the design stage. On the other hand, dwelling on the broad definition for so long may slow down the design process and result in an unnecessary or costly overdesign. The key to overcome these issues is by making all relevant information available to the design team.

The failure to establish a broad definition of the problem can be fatal in some situations. The design of safety automobile airbags clearly demonstrates this point. In this product, specific definitions of the problem were well established, and optimum solutions were provided. However, surrounding factors that are outside the specific functional boundaries of the product were largely neglected. As a result, safety problems occurred after the product was used in the marketplace for quite some time.

With regard to specific definition of a problem, this should also be established with full awareness of the surrounding and probabilistic factors that may come into play even in the most remote situations. One of the examples that best demonstrate this point is the Supersonic Concorde airplane. This giant product was commercially introduced in the mid-1970s. It was a result of joint efforts by companies representing major industrial countries such as France and the United Kingdom, with the idea being very fast (under 4-hour flight time between New York and Paris) and comfortable (no atmospheric turbulence at the very high altitude, 18,000 m, at which it flies). Concorde's take-off speed was 397 km/h compared with a typical subsonic aircraft take-off speed of 300 km/h. This aircraft typically accelerated to supersonic speed over the ocean to avoid a sonic boom over populated areas. It also flew at 2179 km/h (2.04 mach), which was just over twice the speed of sound and the range of the aircraft was about 6580 km.

The Concorde was associated with many specific problems that required accurate definitions and specific solutions. Two of these problems were (a) the ability of the fuel tank to withstand an external impact hit without rupture and (b) the puncture resistance of the tire by sharp metal objects. These two problems represented unusual situations that hardly occur under normal take-off, landing, or flying conditions.

The relationship between these two problems is that the tires in the Concorde were in dangerous proximity to the engines and engine inlets as well as the fuel tanks. Unusual as they may seem, the failure to define these specific problems in the design phase has resulted in a major disaster that eventually led to the end of the Concorde aircraft business. On Tuesday, July 25, 2000, the very first fatal accident involving Concorde occurred with Concorde 203, F-BTSC out bound from Paris to New York. It crashed 60 s after take-off as a result of suffering a tire blow out that caused a fuel tank to rupture. All 100 passengers and 9 crew on board were killed. Four people in a local hotel on the ground were also killed. As indicated earlier, it is always less costly and less damaging to fail early than late.

As it is always the case, diagnosing the cause of failure of the Concorde aircraft necessitated a complete reassembly of the aircraft to determine causes and effects, which costed millions of dollars. One of the reported causes of the Concorde crash was that as the plane was on its take-off run, a metal piece (a titanium strip that fell from another aircraft) punctured the tires, which then burst, puncturing the fuel tanks and leading to an aircraft flying in flame. After the crash, some design efforts were made to correct these problems. These included more secure electrical controls; Kevlar lining to the fuel tanks; and specially developed, burst-resistant tires. Unfortunately, these efforts failed to recover passengers trust in the Concorde aircraft and on May 2003, the last Concorde flew from Paris to New York, and the final flight was back to Paris the next day.

The examples earlier clearly demonstrate the importance of establishing broad and specific definitions of the design problem. They also demonstrate a key aspect of design, which is failure analysis [3]. A design process of a justifiable product idea should involve a problem statement, which expresses what the design is intended to accomplish. Critical points of this statement include the following: objectives, goals, definitions of technical terms, limitations and constraints associated with the design, possible probabilistic outcomes, and criteria that will be used to evaluate the design outcome. Initially, these points may be stated based on the experience of the design team. As more information is gathered and perhaps after the second or third iteration, more detailed problem statement should be made.

4.4.3 Gather relevant information

In general, a solution of a design problem requires special tools that may stem their effectiveness from knowledge of basic aspects in physics, chemistry, and mathematics and their extensions into materials science, solid and fluid mechanics, thermodynamics, transfer and rate processes, and systems analysis. In addition, each design process requires gathering of specific information related to the problem in hand. The amount of information needed will depend on the degree of complexity of the problem and the extent of previous background of the nature of the intended product; the more complex the problem is, the more information will be required to handle the problem.

When the design goal is to modify an existing product for the sake of achieving better performance, a great deal of information should already be available, and the task in this case will be to seek the most relevant, most specific, and most current

information. Sources of this information may include technical reports of sponsored projects, company technical documents, patents, supplier catalogs, and trade journals. Another critical source of information is investigative reports associated with failure or deficiency in pre-existing products. On the other hand, when the intended product represents a new innovation, information may be limited, and expert inputs may have to compensate for the lack of information.

In seeking information relevant to the design problem, an "information priority list" should be made to ensure that the information gathered will be efficiently useful. The broad and specific definitions of the problem should represent the driving issues in this list. In other words, the problem definition statement should guide the design team to the type of information to be gathered and hopefully the sources of information. Other key points on this list will include the following: authenticity, credibility, and accuracy of information and ways to interpret the information.

4.4.4 Design concept formulation

As shown in Fig. 4.3, the previous steps lead to a key question which is "does the current state-of-the-art warrant further efforts with potential added success?" Addressing this question provides additional justification to the merits of the design project. Unlike the first justification step in which participants included engineers, manufacturers, and marketing personnel, this question is addressed by the design engineers and supported by relevant information and a clear definition of the design problem. A "no" answer to this question may result in terminating the design project. A "yes" answer, on the other hand, would mean that the product idea is justifiable, clearly defined, and current information is available and indeed warrant further efforts with potential added success. This leads to the conceptualization step, in which the key question is: "Can ideas be generated for an optimum solution to the problem?" It is at this stage of product design that different design teams may follow different approaches depending on the level of creativity and imaginative talent of the team. The key difference will be on how the design team forms the design concept. In this regard, four basic problem-solving and mind tools can be used for assisting engineers in design conceptualization projects. These are the following: creativity, brainstorming, decision-making, and concept optimization methods.

Forming a design concept does not necessarily mean finding a final solution; it is rather finding an idea for a solution or a direction of thought as some design problems may be associated with numerous solution ideas, and others may indeed have limited or no apparent solutions for example, if the proposed idea is to design a military uniform that can be used under various environmental conditions (from hot to cold and from dry to wet). Provided that a need exists for such a product and the multiplicity of problems associated with achieving these conflicting conditions are defined, the design concept may be formulated in different ways. One concept would perhaps to think in the direction of multiple fabric layers that can be added or removed in accordance to the surrounding conditions; another is to think in terms of impregnating smart phase-change polymeric components that can react to surrounding temperature changes, and another is to think in the direction of utilizing a special fiber blend

supported by unique yarn and fabric structural features. These are not specific solutions as they only represent design concepts expressed in broad terms that can be followed so that analytical efforts can be directed toward fulfilling them in part or in full.

Most design concepts are expressed in qualitative terms with minimum constraints associated with cost, resources availability, or even absolute realism. As Robert Mann described it [6]:

> *Concepts should be considered as possible solutions to engineering challenges arise initially as mental images which are recorded first as sketches or notes and then successively tested, refined, organized, and ultimately documented by using standardized formats.*

The process of forming a design concept often results in revisiting the preparatory tasks discussed earlier as new justifications may surface and more important problems may arise, requiring the establishment of more specific definitions. It is also possible that through the brainstorming process of design conceptualization, the design team finds themselves lacking important pieces of information that must be acquired to continue with the process. The point to be emphasized here is that the design process is not a linear or one-way process. It is an iteration process that should be implemented in the most flexible fashion yet constrained by time and financial resources.

4.5 Bridging from design conceptualization to design analysis

Engineering design is the iterative process of solving engineering problems for the sake of finding an optimum solution that satisfies the performance and economical needs of a product. Design analysis consists of specific analytical tools and procedures required to satisfy the design concepts and meet design objectives. The foundations for design analysis are the outcomes of design conceptualization. It is through design conceptualization that engineers determine the objectives of design analysis, the complexity of a product, the different resources required, and the analytical tools needed to build a product prototype. In today's computer era, numerous analytical tools can be used in design analysis. These include [3] modeling and optimization techniques using computer-aided design and 3-D printing, statistical analyses, neural network, genetic or evolutionary algorithms, simulated annealing, and finite element analysis. At this point, it is important to distinguish between design conceptualization and design analysis. Some of the differences between these two tasks are listed in Table 4.1. Examining these differences almost call for a dual discipline within each engineering program: conceptual discipline and analytical discipline. Alternatively, design conceptualization should represent an essential course in engineering education, divided into two parts: design conceptualization part I, an introductory course offered at the pre-engineering level, and design conceptualization part II offered in parallel with the capstone design project at the senior level. Unfortunately, in most

Table 4.1 Basic differences between design conceptualization and design analysis [3, 6].

Aspect	Design conceptualization	Design analysis
Goals	Generating ideas for an optimum solution to the design problem	Reaching optimum solutions via performing appropriate analysis to satisfy the concepts established
Qualifications	1. Creativity 2. Great communication skills 3. Knowledge in all aspects of product development 4. Abstract knowledge in applied mathematics and natural sciences 5. Experience in problem-solving and decision-making approaches 6. Knowledge in market research 7. Knowledge of user's perspectives of product attributes	1. Good background in applied mathematics, physics, chemistry, statistics, and engineering science (fluid mechanics, thermodynamics, etc.) 2. Good knowledge in graphic engineering (computer-aided design and imaging software) 3. Good computer background 4. Good communication skills 5. Patience and endurance and persistence 6. Cautious but fear robust
Outcomes	1. Idea(s) for solutions 2. Problem definitions 3. Justification points 4. Critical design parameters 5. Possible constraints	1. Optimum solution(s) 2. Product model
Tools	1. Creativity tools 2. Brainstorming tools 3. Decision-making tools 4. Concept optimization tools	1. Software programs 2. Graphing tools 3. Modeling tools 4. Optimization tools 5. Specific analytical tools

engineering programs, students do not get to realize the differences between design conceptualization and design analysis until perhaps the last semester when they are involved in their capstone design project. As a result, students tend to neglect all factors related to design conceptualization and focus on what they know best, which is design analysis.

For readers who are not familiar with capstone design projects, the term "capstone" is derived from architectural engineering to describe a competition of a building or monument [7]. This term has been adopted by engineering education programs since the mid-20th century and endorsed by engineering accreditation organizations. The concept of a capstone design project was initiated for the purpose of connecting engineering students with real-world design applications. Typically, specific procedures are established to guide capstone design projects. The choice of a design

problem in a capstone project varies widely between engineering programs. Many engineering programs use classic design problems that have been solved in the past to give to their students with the hope they can find additional optimum solutions. This approach may be useful under the time constraints associated with the design project. Typically, the faculty advisor supervising the design project is fully aware of few solutions to the problem, and he/she may encourage students to find alternative solutions that are more optimum than the previous ones. This is a valid approach on the ground that engineers in the real world do not get to choose design problems; instead, they deal with problems as they come. The problem with this approach often stems from faculty advisors dictating solutions to the design problem or hindering students from thinking freely without fear of being penalized. This approach largely simulates what happens in the real world when senior engineers authoritatively run the design project and dictate their thoughts on beginner engineers. Other engineering programs implement better capstone design projects by allowing their students to go out and solicit design ideas of their own to business corporates or search for ideas that those corporates are willing to share with them. This type of capstone projects is often implemented via student internships coordinated between the university and external organizations.

Irrespective of the approach of a capstone design project, the following criteria should be met [7–10]:

1. Project selection is the most critical aspect of capstone design. The topic must be carefully selected to provide the appropriate level of challenge and to promote student engagement and motivation.
2. Students should be motivated to perform project tasks.
3. Design problems must be based on conceptualization aspects.
4. Design problems must be open ended in terms of functional and economic solutions, and both optimum solutions and alternative solutions must be described.
5. A design methodology must be described by students, and the choice of analytical tools must be justified.
6. Design problem solutions should be based not only on student's analytical skills but also on creativity.
7. Project team management and communication must be evaluated.
8. Frustration and failure incidents should also be described.

The iterative analysis of design problems can be time consuming and monetarily costly. This brings up the issue of efficiency of design analysis, which is determined by the time required to complete a design project from design conceptualization to design analysis. Since design is only one element of a large product development process, it is important to determine the relative time contribution of design to the overall product development process. For truly new and creative ideas, the design phase may indeed take significant time of the product development process. When only modification of an existing product is required to develop a new and improved version of the product, the design process may consume less time as knowledge of the current product performance and realization of the necessary modifications are typically adequate to perform efficient analysis. In this regard, the so called resource-time elapse profile should be used to evaluate the relative time contribution of the design process to the overall product development process [6].

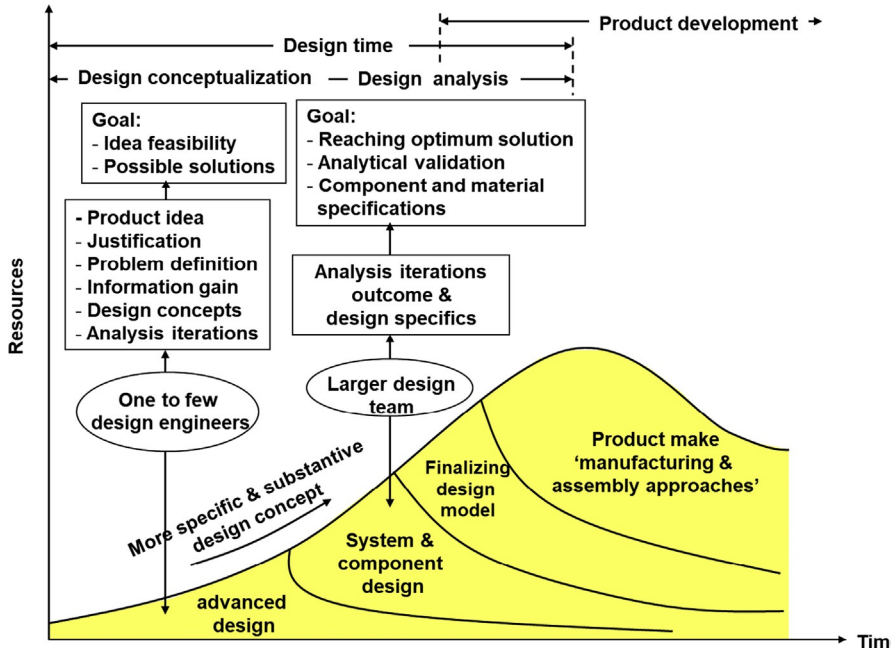


Fig. 4.4 Resource-time elapse profile.
Modified after R.W. Mann, Engineering Design, in AccessScience@McGraw-Hill, http://www.accessscience.com, Last modified: January 11, 2002.

As shown in Fig. 4.4, a resource-time elapse profile clearly describes the elapse of time and expenditure of worker effort in the evolution of a product development project. In this regard, design time duration is divided into two periods: the period for design conceptualization and the period for design analysis. The vertical axis represents the available resources. In the conceptualization phase, these are mostly human resources that are typically available within an organization. Over the years, the time required to perform design analysis has been reduced significantly due to the availability of computing power and capable software programs. However, this process still requires many tasks and significant resources than that of design conceptualization. Typical tasks include trying different materials, testing and validation, and product model assembly, but the most significant time is that consumed in finding optimum solutions. Organizations with higher resource curves will likely to meet the design objectives in less time than those with lower resource curves. By the time the product model is at its finalization stage and as the product enters the manufacturing phase, resources are typically at their maximum level. Thus, the merit of implementing a resource-time elapse profile is to establish a timeframe for meeting the task of design with respect to the total time consumed in product development.

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Engineering design in the textile and garment industry

5

5.1 Introduction

Engineering design is generally defined as an iterative process of solving engineering problems for the sake of finding an optimum solution that satisfies the functional performance and the economic needs of a product or service. An engineering design project must begin with the process of design conceptualization in which all aspects associated with the intended product or service are predetermined, and the design problem is identified and initially defined. As indicated in Chapter 4, design conceptualization is achieved using a wide range of qualification including engineers, technologists, economists, marketing personnel, and consumer experts. It is essentially a team work that can be headed by a product development manager to coordinate the different efforts made by the different personnel involved in design conceptualization. Once a design concept is established, the ball is moved to the engineering field where design analysis is performed to reach optimum solution and develop a product prototype. Depending on the complexity of the problem and the extent of sophistication of the intended product or service, many analytical tools may be used ranging from a simple sketch of a product model on a drawing table to more advanced computer-aided design tools that allow design analysis to be efficient while satisfying the technical requirements of a product. The success of a design analysis is determined by the extent of meeting the desired product model (construction and shape) and the intended functions of a product at the highest-performance efficiency and the lowest cost possible.

The earlier introduction of engineering design implies a complex process in which a great deal of scientific backgrounds and high analytical skills is required. This makes the design analysis exclusively an engineering job. For this reason, engineers undergo rigorous education programs in which they learn many scientific subjects including calculus, differential equations, physics, thermodynamics, fluid mechanics, statistics, and economics. A puzzling question at this point is how the early craftsmen were able to design products, systems, and equipment that had served the world for thousands of years way before engineering became a scientific discipline; how much knowledge those craftsmen had in physics and mathematics; and what analytical skills and tools they had.

Throughout most of the 19th century, engineering design in most industries was primarily based on art, experience, individual creativity, and trial and error. The textile industry, which led the industrial revolution in the 18th and 19th centuries, represented a perfect model of intellectual craftsmanship. Textile machinery was one of the early types of machinery that were transformed from hand operated to power operated.

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Textile products such as yarns, fabrics, and garments were made using classic approaches that were developed hundreds of years earlier. Old designers, or perhaps, better called craftsmen, did not draw their products before building them and were often unable to explain satisfactorily why they did things the way they did; it was all in their memory, which was refreshed by keep trying different things [1]. Some machine inventions in the textile industry took many years before they were finally developed into efficient production machines, and it was all by trial and error, a costly process of a continuous search for the missing pieces of the design puzzle until a good product was made. The whole process of early design analysis was largely qualitative, and early craftsmen fully realized many aspects of design conceptualization as many of them were also textile manufacturers and traders.

In view of the earlier points, one can classify the evolution of engineering design into two main eras: (a) the before-powered-machine era, which was the era prior to the industrial revolution, and (b) the powered-machine era, which began during the industrial revolution and continued until today. In the first era, engineering scientific disciplines were not in full existence, and all design analyses were represented by the work of creative individuals who relied primarily on their own experience, some knowledge from classic science, and repeated trials. During this era, fundamental science was still scattered, and research activities were at a narrow scale. The second era was driven by the discovery of power to run machines and to design more complex mechanisms that can provide higher efficiency and produce more sophisticated products. Scientific disciplines such as mechanical and electrical engineering were in their way to be fully established. This transition had occurred while the world population was growing from about 750 million at the beginning of the industrial revolution (1750) to 1.2 billion people in 1850.

As discussed in Chapter 2, the textile machinery industry played a major role in the powered-machine era. Indeed, concepts such as high production efficiency and the transition from semiautomated to fully automated machinery were pioneered by this industry. Even the early concepts of information technology were discovered by the textile machinery industry. In the postindustrial revolution era, it seems that while many other industries had taken off substantially in terms of innovative machine design and quantitative design approaches of various products, the textile industry had decided to dwell on its previous gains and focus primarily on production as the only way to achieve economic survival. According to Hearle [1], while other industries marched into the second half of the 20th century utilizing more quantitative design approaches inspired by the growth of the science of applied mechanics and the theory of elasticity, these approaches were not transformed to the textile industry, which continued to implement empiricism and augmented the qualitative insights in its product design applications, with one exception being the mechanical and power-driven design of textile machinery. He pointed out many specific reasons for the lack of quantitative design in the textile industry. The first reason was what he described as industry's conservatism. The second reason was the lack of absolute necessity for quantitative design of textiles as a result of moderate consumer's expectations in terms of safety and functional performance. As he described [1]:

> *…bridges must be built so that they do not fall down; aircraft must fly; the structures are large; the costs are high; performance continually need to be increased; and the design process for new models is long. Quantitative engineering design is needed for safety and to optimize cost benefits. In contrast to this, most textile products are small scale; individual costs are low; failure in a trial is a nuisance but not a disaster; and design time is short.*

The focus of this chapter will be on engineering design in the textile and garment industry. Key obstacles facing full implementation of engineering design in the textile industry are discussed, and ways to overcome these obstacles are proposed. In addition, a design system will be proposed to illustrate the basic steps of engineering design and the importance of distinguishing between design-problem models and design-solution models.

5.2 The role of textile science in the development of the textile industry

As discussed in Chapter 4 under the subject of "engineering operating system (EOS)," engineering design represents the vehicle that transform science to technology. Engineers use science to convert idealized and applied concepts into real products or process models. Technology can then take these models and convert them into physical products through semisystematic manufacturing approaches. In Chapter 3, we discussed the importance of science in the engineering world and the differences between science and engineering. The textile industry being one of the oldest industries in the world demonstrated the art of know-how at a time textile science was not in existence and the rules of engineering design were not established, and technology was only what a human hand can do. It was all about human's creativity and the know-how. This was all acceptable in the era before powered machines were invented. After the development of powered machine, it was important to bridge science, engineering, and technology to assure reliable functionality at high production rates. That is when the textile industry needed a great deal of science to move forward with new designs and better technology. The role of science in the development of the textile industry is demonstrated in the brief overview presented in the succeeding text.

Scientific research in the textile field had markedly begun in the early years of the 20th century [2–6]. The focus of the early studies was on understanding the chemical composition and the physical structures of fibers. For example, William Lawrence "W.L." Balls (1882–1960), a British botanist who was educated at Norwich School and at St John's College, Cambridge, was one of the first scientists to study the development and properties of raw cotton [3]. His book titled *The Development and Properties of Raw Cotton* published in 1915 was the reference on cotton at that time. The content of this book was driven by a significant research that Balls conducted on the Egyptian cotton. Recall that the first idea leading to the development of man-made fiber was proposed in the 17th century by Robert Hooke. This idea was not materialized into commercial man-made fiber until the early 20th century

when Courtaulds Ltd. USA produced the first commercial viscose rayon as a result of significant research work by Charles Frederick Cross (1855–1935), a British chemist who worked tirelessly with his research team to discover the viscose process [4]. In the mid-1930s, another historical research finding was revealed by DuPont Chemicals research laboratory [5]. This was the first nylon fiber introduced to the world based on extensive research led by Wallace Carothers (1896–1937), an American chemist, inventor, and the leader of organic chemistry at DuPont. On the textile end-product side, one of the outstanding examples of scientific research was the work by Ruth Mary Rogan Benerito (1916–2013), an American chemist known for her work related to the development of wash-and-wear or wrinkle-free cotton fabrics using the principle of "cross-linking" process and monobasic acid chlorides [6].

The research activities discussed earlier represent examples of science that has immensely served engineering and technology in the textile industry and perfectly closed the loop of the EOS system. The development of new fibers resulted in the design of many traditional and technical textile products that had far exceeded the performance of products made prior to the 20th century. It has also resulted in the design of new textile machines that are capable of producing and processing synthetic fibers and different natural/synthetic fiber blends at the highest efficiency possible.

In parallel with the types of research discussed earlier, scientists of many textile institutes around the world were also contributing to textile science through exploring many areas including the functional capacity of different fibers, the structural and physical properties of fibrous structures, and the functional characteristics of textile fabrics. Many of these studies were published in distinguished international journals including the *Journal of Textile Institute* (1923–present), the *Textile Research Journal* (1930–present), and the *Journal of Applied Polymer Science* (1959–present). These journals are still published today drawing millions of readers from the scientific community around the world every year. It will also be useful to honor some of the top scientists in the field that have contributed to what is now called "textile science." Some of these scientists are listed in the succeeding text.

In the period from 1920s to 1940s, an Australian scientist by the name Frederick Thomas Peirce had contributed immensely to the field of textile science through numerous scientific studies in many areas including [7–15] water absorption of textiles; handle of cloth; the geometry of cloth structure; the serviceability of fabrics in regard to wear, fineness, and maturity of cotton fibers; measurements of the water vapor permeability; transmission of heat through textile fabrics; geometrical principles applicable to the design of functional fabrics; and the plasticity behavior of fibers. The significant contribution of Peirce to the field inspired many great scientists in the latter years including Hearle and Morton who wrote a book on the physical properties of textile fibers [16] published in 1962. This book still represents a reference cited by numerous textile and fiber scientists around the world. Another book published in 1969 by Hearle, Grosberg, and Stanley Backer of MIT titled *Structural Mechanics of Fibers, Yarns, and Fabric* [17] dealt with many fundamental aspects of the mechanics of flexible fiber structures. John Hearle then went on to contribute immensely to the area of textile mechanics [18–21] from the early 1960s until his death in 2016 at the age of 90.

Sueo Kawabata (1931–2001) of Kyoto University, Japan, is another distinguished scientist in the textile field who contributed significantly to the research on solid mechanics of polymeric materials, including rubber, composites, and fibrous materials. In the 1970s, he developed his own system of fabric evaluation, known as Kawabata Evaluation System (KES) [22, 23]. This system was used in many research laboratories around the world to test fabric tensile and shear stress, bending stiffness, compressional behavior of fabric, and surface friction and fabric roughness. Kawabata also developed a technique for performing micromeasurement of the mechanical properties of single fibers. He was a scientist with a clear mission, which is transforming the old practice of subjective evaluation of fibrous structures into more objective means supported by well-designed testing equipment. Another great scientist is Witold Zurek of Poland, who contributed immensely to the analysis of yarn structure, and his book on the structure of yarn [24] was translated from Polish to English by the US Department of Agriculture in 1975. The significant dimension that Zurek added to textile science was the detailed analysis of the stochastic discrete nature of fibers. He also built his own research empire in Poland and assisted scientists around the world in understanding many key aspects including the elastic properties of twisted monofilaments, the abrasion resistance of cotton fabric, and surface frictional resistance of fabrics woven from filament yarns.

The impact of textile science has been mostly realized by the synthetic fiber industry and more recently in the area of technical textiles and smart fashion. This is a direct result of the existence of research and development (R&D) departments in these industries. As to the traditional textile industry, which is about 85% of the entire industry, utilization of scientific research has been limited, and the transformation of science into engineering design applications has been slow. In the following two sections, engineering design perspectives in the global traditional textiles and fashion industries will be discussed. We will then discuss ways to move the traditional industry forward in terms of engineering design.

5.3 The status of engineering design in the traditional textile industry

The traditional textile industry is the industry dealing with the conversion of fibers into fabric. As shown in Fig. 5.1, fibers can be of natural, synthetic, or specialty fibers that are also synthetic fibers but made for special performance applications. Fibers may also be categorized into staple fibers, which are of discrete nature and short lengths, or continuous filaments, which consist of very long monofilament or multifilament. Fibers can be converted into fabrics using two different categories of processing: (a) direct fiber-to-fabric process in which fibers are essentially compacted and bonded into nonwoven structures and (b) indirect fiber-to-fabric process in which fibers are first converted into a yarn using a spinning process and yarns are then converted into fabric which can be knitted or woven. The term “traditional” stems from the fact that the processes described have been used in principle for hundreds

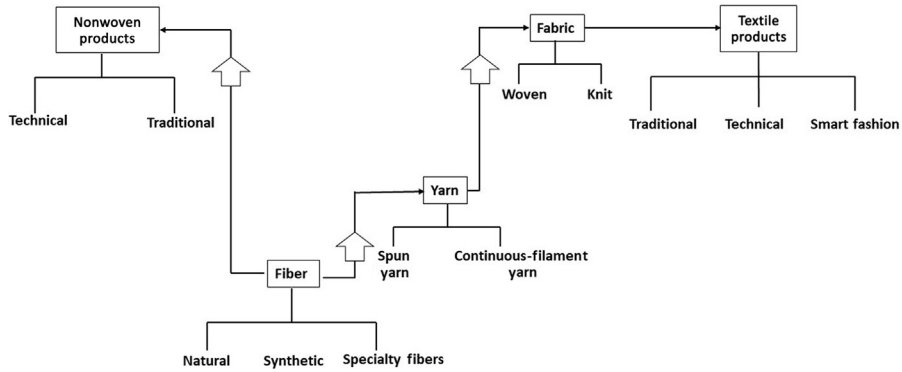


Fig. 5.1 The general flow of fibrous materials.

of years to make masses of textile fabrics that can be used in numerous types of textile end products.

This sector of the industry has relied for hundreds of years on supporting technology to produce products. The concept of design in this sector has always been based on what the early scientists and inventors had developed in terms of the methods of manipulating discrete fibers into continuous fiber strands, the binding mechanisms of staple fibers (twisting or wrapping), and the principle of fabric forming by interlacing or interlooping of fibrous threads. As a result, the formation of products has always been based on classic principles with little room for changes unless a new technology imposes a change. In the context of the EOS system described earlier, the common practice of the traditional industry has been to go directly from science, which is essentially reduced to the "know-how" straight to technology represented by textile machinery. The term engineering design has hardly been used in the development of products in the traditional textile industry, and even when the term "design" is used, it only implies qualitative approaches of processing or systematic patterns of fabric.

Most traditional textile products are very familiar by virtue of the massive number of users, and they are also highly predictable in terms of their basic functions and methods of maintenance. This is perhaps why John Hearle attributed the lack of quantitative design in this industry to conservatism and a lack of absolute necessity for quantitative design of textiles as a result of moderate consumer's expectations in terms of safety and functional performance. However, based on the author's experience with this industry, there are many other reasons why the traditional industry has not implemented quantitative design for many years. These reasons stem from the historical structure and the management and marketing approaches of this industry that are briefly reviewed in the succeeding text.

In the second half of the 20th century, while the industrial world was moving more toward the product-focus era, the traditional textile industry remained in the production-focus era. In the last quarter of the 20th century, the world's population exploded from 4 billion people to over 6 billion people, and globalization began to dictate new marketing and trade strategies. In the face of the increasing world's

population, the traditional textile industry found new opportunities to continue heavily in its production-focus strategy by utilizing technologies that can assist in making masses of products. However, obstacles such as labor cost and product consistency had to be overcome. The textile machinery maker came to the rescue through adding key design features such as automation, high production speeds, transportation, and process condensation. This was a new turning point in the design of textile machinery, particularly in industrial countries such as the United States and Europe that found these developments great opportunities to survive a little further in the face of growing competition of developing countries that had substantial advantages in labor cost.

The 21st century came with new challenges to the traditional textile industry imposed by progressive and aggressive globalization fueled by substantial labor cost differences between industrial countries and developing countries. As a result, the 21st century marked the beginning of a significant shrinkage in the traditional textile industry in Europe and the United States and significant growth in Asia, particularly China and India. According to the World Trade Statistical Review 2018 by the World Trade Organization [25, 26], in 2017, the dollar value of world textiles and apparel exports totaled $296.1 billion and $454.5 billion, respectively. In the 2000–17 period, the US export share of textiles was reduced by 35%, reaching only $14 billion in 2017, while China's export share of textiles was increased by a stunning 257%, reaching $110 billion in 2017. In the same period, the US export share of clothing was reduced by 73%, reaching only $6 billion in 2017, while China's export share of clothing was increased by 92%, reaching $158 billion in 2017.

Although it seems that these significant changes in the traditional textile market were a direct result of apparent economic factors, primarily labor cost, it is the author's opinion that these changes were inevitable in view of the classic approach that the traditional textile industry has taken over the years, which is production focus and technology driven by mass production and higher speeds. This approach had also affected the design of textile machinery making it largely oriented toward more production-focus functions including automation to reduce manpower, high production rates to increase outputs, more machine linking and direct transportation of materials, and automatic process control. These developments are undoubtedly great features, and they involve advanced engineering design methods, but they did not directly lead to the design of new textile products or solve traditional quality problems of textile products. Arguably, some of these machine design developments were at the expense of quality problems including [27, 28] higher fiber damage; creation of unwanted defects such as mechanical neps and fragmented microtrash particles; and rapid wear out of machine parts such as card wires, rollers, travelers, and belts. In addition, automation and automatic process control required labor skills that the industry was not fully able to provide. As a result, the economic benefits of these new machineries have not materialized in industrialized countries, and by the 10th year of this century, the traditional textile industry was largely displaced from these countries.

A logical question at this point is what the traditional textile industry would have done differently in industrial countries to maintain its survival and perhaps prosper. Today, this seems like a very difficult question to answer, but the industry has been

warned from these consequences for many years prior to the decline. The author of this book is highly confident that the key solution was through engineering design. Indeed, the remaining industry in the United States is now implementing many design approaches that are assisting them in staying in business and accomplishing profit. A yarn or fabric should be designed out and not merely manufactured out using conventional methods. This means establishing engineering design approaches in critical areas including [27–34] fiber selection and fiber blending, modeling fiber-to-yarn and yarn-to-fabric relationships using exploratory and prediction models that can assist in determining key attributes contributing to the desired yarn or fabric characteristics, modeling fiber/machine interaction, integrating inherent quality problems into the design-problem model, integrating functional characteristics into the design-solution model, and integrating the quality/cost trade-off in every aspect of the product manufacturability. These represent only few examples of numerous aspects that have been covered in textile science waiting for the industry to make use of their contents and merits in integrated design approaches of products.

As indicated earlier, one of the common terms used in the fabric segment of the industry is "fabric design," which is typically used to describe fabric patterns (i.e., for woven fabrics, plain weave, twill weave, etc., and for knitted fabrics, single jersey, interlock, etc.). It may also mean different printing designs. These designs are produced using systematic mechanisms and adjustments of the weaving and knitting machines. Scientific research has provided numerous approaches to use different fabric patterns in conjunction with fabric construction parameters (e.g., fabric thickness, cover factor, and fabric density) for the sake of producing fabrics of different functional characteristics [9, 10, 12–14, 22, 23]. These efforts were not necessarily design oriented, but they provide many exploratory models that can effectively be used as references to engineering models. Unfortunately, fabric designers and manufacturers in the traditional textile industry made little use of the outcomes of these efforts, and many outstanding publications in this field never made it beyond the scientific archives or remained embedded in intellectual properties that were never used.

The dyeing and finishing sector of the traditional textile industry has been the most active segment in implementing engineering design aspects [35–42]. The dyeing process provides many color and appearance options that are critical in satisfying style and appearance features of textiles. Different fibers require different types of coloring agents that are chemically compatible, which means that dyeing chemical must be engineered in and colorfast must be carefully designed to avoid fading of color as a result of exposure to sun or upon repeated washing and drying. The process of dyeing textiles involves many options including fiber dyeing, yarn dyeing, or fabric dyeing. Furthermore, many methods of dyeing can be used including piece dyeing (dyeing the fabric after it is woven or knitted), roller dyeing (color applied to fabric as it goes through a series of rollers), fabric printing (adding color, pattern, or design to the surface of fabric), screen printing (applied on flat screen frames with each color has its own screen), rotary screen printing (a combination of roller and screen printing), heat transfer printing (transferring patterns from paper to fabric by pressurized heat setting), digital printing (using computer-controlled droplets of color), and garment dyeing. These represent many options that a design

engineer can utilize in finding optimum solutions of design problems associated with color and surface patterns.

Textile finishing is the process of applying chemical and mechanical processes to the greige fabric to produce desired aesthetic or functional effects [35]. In the context of engineering design, the finishing process can assist in solving numerous design problems, particularly those associated with inherent deficiency in the fabric structure. The primary aspect of finishing is cleaning the fabric and removing impurities that might remain from previous manufacturing process. This is an inevitable technological process that consumes significant amount of water. Another common process is fabric bleaching, which provides a white background surface and removes inherent colors. Scouring is another finishing process in which heat and detergents are used to remove dirt, grease, and wax. In the case of cotton fabrics, mercerizing is a common finishing process in which fabrics under tension are submerged in a sodium hydroxide solution for short period of time and then rinsed. This process makes cotton fabric stronger, gives it a lustrous or shiny surface, and improves its ability to take dyes and hold more vivid colors. These are all design options that can be considered in solving many problems. Many fabrics tend to shrink after water or chemical treatment, which necessitates stabilizing treatment to control fabric dimensional stability. This may include "calendering," which compacts fabric fibers by pressing them between two large heated rollers. With respect design, many finishing agents can be used to enhance many fabric performance characteristics including wrinkle resistance, antistatic, water repellency, flame retardation, and antibacterial. In dyeing and finishing woven fabrics, "tentering" is a critical process in which the warp and weft of woven fabrics are stretched and set at right angles to each other using chains traveling on tracks fitted with pins or clips to hold the selvedges of the fabric. As the fabric passes through a heated chamber, creases and wrinkles are removed, the weave is straightened, and the fabric is dried to its final size. Although these may be considered as manufacturing aspects, they indeed contribute immensely to solving many design problems of textiles.

The dyeing and finishing industry has been faced with so many challenges that certainly require a fundamental change in its design culture. The industry still relies on intense labor, which is not only a significant cost factor (more than 40% of the cost) but also associated with labor exposure to toxic chemicals and unsafe environment. More than 6% of the cost of this industry is water cost, and 12% is energy cost, the cost of dyestuffs and chemical amounts to about 29%, and the remaining cost is distributed between environment and safety measures and maintenance [35, 38]. From an engineering technology perspective, the industry must continue efforts to reduce water and energy consumption, reduce processing time, allow varying load capacity, and optimize the rinsing processes. By today's standards, an industry that consumes more than 100 L of water to dye 1 kg of cotton fabric is considered unsustainable [36]. Therefore, continuing efforts including the use of trireactive dye range for cellulosic fibers are utilized to reduce water consumption. It is well known that most reactive dye molecules have one or two reactive groups that bond with the fiber and remain permanently fixed. Dye that fails to bond is hydrolyzed and cannot be fixed on the fiber. In conventional dyeing, 20%–40% of the dye

molecules typically are hydrolyzed. To achieve highly colorfast fabrics, unfixed dye needs to be fully removed, which is a long, hot, expensive, water-intensive, and energy-intensive process. Efforts are also being made to recover a great deal of heat used in the drying and setting process and, thus, reduce energy consumption.

In view of the earlier points, dyeing and finishing carry a heavy design burden with respect to sustainability aspects. Further details on sustainability will be discussed in Chapter 6. Fortunately, there are many ongoing design efforts to create a sustainable dyeing and finishing industry. New dyes are being introduced that are, for instance, free of halogens and heavy metals in new chemical structures with very high exhaust and fixation values. This permits a great deal of compliant with today's ecological and technical requirements. Dyeing without water and with no effluents using supercritical carbon dioxide, CO2, dyeing [39] represents unique design idea toward sustainability. Compared with standard aqueous dyeing methods, the supercritical carbon dioxide process leads to strongly reduced water and energy consumption and a shorter dyeing time. In the case of polyester, high dye fixation and good levelness can be achieved without disperse dye formulating agents or dyeing auxiliaries. The carbon dioxide used in the process has the advantage of being nontoxic compared, for example, with solvent dyeing methods and can also be recycled to a very high degree.

5.4 The status of engineering design in the fashion industry

The term "design" in the fashion industry is well established in association with the profession of fashion design. A fashion designer is a person who has great passion for fashion trends, sketches creative designs, and transforms design models into fashion clothing. Over the years, fashion design has immensely contributed to the creation of millions of pieces of clothing and accessories and generated trillions of dollars in revenues. The differences between fashion design and engineering design primarily stem from the approaches taken by fashion designers and design engineers in creating a product. To understand these differences, it will be important to first understand how the fashion industry goes about designing a certain fashion [43–45].

Creating fashion consists of three basic steps: art, design, and manufacturing. The fashion industry relies a great deal on artists to create unprocessed objects for fashion designers who can then transform them into product models that are manufactured into fashionable apparels. The functions of artists and designers are often confused in the fashion industry since they both create visuals of anticipated fashions using common knowledge base. However, the fundamental difference is in the purpose and the motivation; an artist is emotionally motivated, and a fashion designer is purpose motivated. An artist starts with a sketching board or an empty canvas and sets his/her emotion free to create art. A fashion designer who is not an artist typically plays the role of communicating an art that already exist into fashion that has the potential to attract customers. This makes good art a creative talent and good design a creative skill, which can be enhanced by education and practice. Most artists do not

think of how their art viewers interpret or feel about their work, but fashion designers must keep their viewers in mind as they represent their potential customers.

A typical fashion designer earns a degree (associate or bachelor) in fashion design or fashion merchandizing. Academic coursework may include the principles of fashion design for different body shapes, fashion trends, garment construction, color theory, textiles, fashion history, visual merchandising, branding, apparel design, computer-aided design, merchandising theories, and marketing. The conversion of a fashion design into an actual fashion product often involves a category of profession called technical designers, which requires an associate or bachelor's degree in fashion design or technical design. In the fashion industry, technical designers are often called the engineers of the fashion manufacturing industry. Once a fashion designer sketches a garment or accessory, a technical designer will figure out how a sketch can be brought to life by creating a technical package encompassing various details for the production team, such as bill of materials, final sketch of garment or accessory, packaging instructions, label or hangtag placement, wash description, sewing details, and points of measurement. The production team will then create a prototype or sample of the proposed garment or accessory, which is checked for any specification issues and then demonstrated to the designer for final feedback.

In view of the earlier points, one can see that there is a great deal of similarity between fashion design and engineering design; they both aim the creation of things; they both start with some form of raw material that must be manipulated to create a product, they both use drawing and sketching to illustrate product models; they both require systematic steps to reach a final product; they both deal with many similar constraints, and the true merits of their outcomes are primarily determined by the extent of creativity in the designed product. Despite these similarities, a fashion designer comes from a completely different education background. While an engineering student must undergo a rigorous education line with many mathematics, physics, and chemistry courses that are often associated with anxiety among most students, a fashion design student may drop all these demanding courses and take up simpler textiles and art education line as indicated earlier. Students pursuing the latter field can certainly find a great deal of inspiration in famous fashion designers including Thomas Jacob "Tommy" Hilfiger, who is known as the champion of star-spangled glamour, yet was only a high-school graduate, or Calvin Klein, a graduate of the Fashion Institute of Technology in New York who started his fashion design career in suits and coats and later became famous for his sportswear line, then moved to the top of the fashion world with a variety of fashion lines, or Michael David Kors, a very famous American fashion designer who joined the Fashion Institute of Technology in New York but never completed his degree.

The points earlier clearly indicate that when the main aspect of design is creativity, education background may be important, but it is certainly not a precondition or an inevitable necessity. Creativity per se is an independent aspect, and it cannot be taught in schools, though many schools attempt to teach it; you can inspire creativity, but you cannot teach it. It is also possible to instill the fundamentals so that a person may go on and hopefully become creative, but no one can teach anyone how to be creative since creativity is not an attribute that can be calibrated against some measurable or control

standards. This issue by itself has been an educational dilemma for hundreds of years, particularly in engineering and science education where students are often demotivated to be creative as a result of the sole emphasis on complex mathematical calculations focusing on the "how" instead of the "what" or "why." This point falls in the heart of debate of whether engineering design should involve art and emotion, or it should remain a systematic approach based on given knowledge with the goal being to reach an optimum solution in terms of functional characteristics and cost. It is the author's opinion that engineers can learn a lot from fashion designers in this regard so that they can reach solutions that are not only optimum but also appealing and beautiful.

The fundamental difference between fashion design and engineering design primarily stems from two aspects [2, 43]: the problem model and the design approach. The issue of problem modeling will be discussed later in this chapter in the context of design cognition. In general, a problem is brought to the attention of an engineering design through either a deficiency in an existing product or system or a need to take functional characteristics upstream through new innovations or disruptive technology. On the other hand, a fashion designer deals with a different category of problems in which he/she must first create a dissatisfaction with a current fashion not because of a functional deficiency but rather because a new and more attractive fashion is due; it is the problem of stimulating and restimulating the consumer continuously and endlessly so that new lines of fashion can be introduced. As a result, the design approach in fashion becomes systematic only after the art and the creative work is completed. In this regard, it should be pointed out that both engineering design and fashion design share the high chance of designs being totally rejected by consumers or receiving minimum appeal. However, this chance is much greater in fashion design than in engineering design as a result of the significant subjective nature of people's attraction to fashionable products and the increasing dynamic changes in consumer's appetite by generation, culture, and demographics.

Historically, the relationship between engineering design and fashion design has been limited to the need to providing efficient technology to the sewing and cutting industry. This has led to continuous improvement in information technology, garment finishing, sewing, and cutting machinery leading to less reliance on skilled labor. For example, today's fashion industry utilizes all sorts of technology in the design and manufacturing of its products including CAD, CAM, manufacturing management, and information technology systems. The many tedious and repetitive tasks in the fashion industry are now handled by robots that are equipped with memory and artificial intelligent systems. Like automation in the traditional textile industry, the use of robots is not about eliminating labor but more about consistency and human safety. The use of robots is still a work in progress with better performance in areas such as cutting and hemming and many challenges in the design of robots that can perform sewing particularly in situations in which pliable or elastic fabrics are used. Robots still have a hard time handling flimsy and stretchy fabric.

To overcome the challenge associated with automated sewing, some companies (e.g., the Seattle Sewbo Inc.) developed sewing robots equipped with robotic arms and air grippers, which can guide a piece of cloth through a sewing machine. However,

the fabric must be molded and welded before being permanently sewn together using a water-soluble stiffener, which is removed at the end of the manufacturing process with a simple rinse in hot water, leaving a soft, fully assembled piece of clothing. The stiffener can then be recovered for reuse. The company demonstrated this invention using a robot capable of sewing a T-shirt without any human intervention (http://www.sewbo.com/press/). Upon further progress, the potential of this technology is tremendous given the fact that the T-shirt demonstrated by the Sewbo Inc. only costed $0.33 to make. Exploring virtual 3-D printing in the fashion industry will provide opportunities for more engineering design in the industry and assist in developing products that are tailored to consumer wants and needs in timely manner. Using 3-D printing, the design of product models can be edited and reviewed immediately after changes are made. Digital knitting is another tool that will certainly increase engineering design of knitted garments. It will provide an ability to turn cones of yarn into a full, seamless garment in a few minutes while considering for functionalities and styles.

The fashion industry has always embraced new fibers and fabric products designed by textile engineers. Indeed, most new developments in fiber, yarn, or fabric products have been adopted by the fashion industry in creating new fashions. Many historians still remember the New York World's Fair of 1939–40, which was one of the greatest expos the world had ever seen. Visitors of this expo were invited to see what was described as the "world of tomorrow" giving them a first glimpse of wonders such as the television, the videophone, and the Ford Mustang. It was also the first chance to see nylon, the world's first fully synthetic man-made fiber. It was being sewn into pantyhose by a display of knitting machines as two fashion models played tug of war to demonstrate the strength of the fabric. Now, many fashions are made from unusual materials including silk-like fiber derived from spoiled milk, recycled plastic bottles, fibrous coconut husks, and raw materials made by fermenting sugar extracted from corn.

5.5 Changing the design culture in the traditional textile and fashion industry

As discussed earlier, the production-focus approach of the traditional textile industry has exhausted its benefits, which lasted over 100 years, and now, the major part of the industry must choose between continuing this approach and accept being tossed around the globe searching for cheap labor and economic survival or becoming a product-focus industry by diversifying itself to serve both price-differential markets and value-differential markets. Only few years ago, the second approach was not a feasible option because of limited market opportunities. Now, the traditional textile industry can find unlimited market channels in two major emerging markets: the smart fashion market and the technical textile market. Smart fashions represent a very promising market, which is likely to grow tremendously before the middle of this century [46, 47]. The technical textile market began growing in the last quarter of the 20th century and is now accelerating its growth rate by the year; it was valued at over

$150 billion in 2016, and it is certain to grow further in the years to come [48, 49]. These categories of textiles utilize fibrous structures (woven, knitted, and nonwoven), they deviate largely from the traditional use of textiles, they have unlimited innovation potentials, and they require significant implementation of engineering design. The difference between the two categories stems from the focus of applications of products in each category. In smart fashions, garments are used as a platform for electronic devices and sensors that are embedded in the fabric structure (woven in, knitted in, or attached) for a variety of purposes including [46, 47] entertainment, safety warning, and monitoring health-related parameters. In other words, smart fashions represent fashionable functional clothing. Technical textiles, on the other hand, cover a very wide range of applications such as geotextiles, medical textiles, autotextiles, filtration and drainage, construction, and protective clothing. Many of these products have been established for years and many more to be innovated.

Innovations in smart fashion and technical textiles have been a result of interdisciplinary efforts by expertise in different fields. The involvement of the synthetic fiber industry in these innovations has been tremendous as newer fibers have always fueled the momentum for more creative designs and product developments. The role of the traditional textile industry has been limited to providing the technology required to produce the necessary fibrous structures (yarns and fabrics) with different chemical and mechanical finishes that meet the specifications required by the designers of technical textiles and smart fashion. Based on the author's experience in these new fields, many design projects of technical textiles and smart fashions were completed with minimum or no involvement of textile engineers belonging to the traditional textile industry, and even those who were involved in design projects largely played the role of textile technologists providing guidelines on yarn type and fabric constructions. We believe that more involvement of textile engineers in the design teams of smart fashions and technical textiles will provide a critical dimension in the design of these products, and it will assist greatly in avoiding many of the fundamental problems that have been witnessed in some of the products that are now commercially available.

Developers of technical textiles often face design issues that are rooted back to the choice of fiber type, inappropriate fabric construction, or wrong yarn structure. These intermediate products are often treated merely as raw materials without paying attention to the fact that themselves can be designed and redesigned to meet different functional and styling requirements of the final product. Indeed, the absence of a holistic design was one of the common observations that we witnessed in many technical textiles. In one of the projects sponsored by an automaker, in which the author was involved, the objective was to compare several car seat designs made of different materials. We tested many car seats made of different materials including nylon seat covers, polyester/cotton fabric, cotton/linen fabric, and wool/cotton fabric. The reference products were genuine leather and neoprene (expensive synthetic rubber material). It was apparent that each type of seat cover provides some advantages and disadvantages particularly with respect to key design features of seat covers such as UV resistance, moisture and stain resistance, breathability, durability, and softness. However, our consumer survey with respect to style and comfort virtually revealed equal responses for all textile seat covers.

In the smart fashion field, similar problems were found as a result of treating textiles as merely a platform in which electronics were embedded. Jill Duffy in her 2016 article in PC Magazine [50] described her experience with some smart fashions in a way that clearly demonstrates this point. She wrote:

> *…. most of the clothes are terrible. By that, I mean that most of the clothes aren't hitting the bar in terms of being clothing I want to wear. The fit is off. Nothing is stylish. And forget about choosing colors or patterns…..Hearing about what smart clothes can do and seeing their sexy advertisements don't actually convey what it feels like to wear them….*

The points earlier should not be viewed as major deficiencies in the design of technical textiles or smart fashions as most of the design efforts in these categories of products are still largely a work in progress. On the other hand, these points clearly indicated that a holistic and integrated engineering design of these products involving textile engineers should be implemented. The future fashion, particularly in smart clothing market, will see more cooperation between fashion designers and design engineers. This will be an inevitable result of the need for a greater interaction between science and technology with design being the vehicle between these two areas. The selection of fibers or fabrics in the fashion industry will merely based not only on colors and styles but also on specific full understanding of the inherent characteristics of fibers and the structural aspects of yarns and fabrics. This will provide many options in functional performances, aesthetic features, and tactile qualities. Science will play a greater role in this area. On the technology side, many aspects will require a great deal of engineering including coating, laser cutting, microfiber handling, shape-memory alloys, and technical clothes. Therefore, new innovations in fashion will be largely hybrid in terms of functionality and style. As a result, the fashion industry must borrow many of the design conceptualization aspects that have been implemented by engineers for many years. Currently, the distinction between garment design and fabric design becomes blurred when one examines the aspect of design conceptualization [43].

5.6 Textile engineering design system (CMOM design system)

Design analysis is essentially a decision-making process in which analytical tools derived from basic sciences, mathematics, statistics, and engineering fundamentals are utilized for the purpose of developing a product model that is convertible into an actual product. The type of analysis required will depend on the product concept established, performance specifications of the actual product, and desired - application(s). In general, a product model should meet four basic criteria [2]: (1) resemblance of a design concept, (2) visibility and predictability, (3) optimum functional performance, and (4) manufacturability. In practice, these criteria are typically met through a multiplicity of processes that collectively represent a design project. In the design of textile products, these processes often represent scattered tasks

performed by different personnel including engineers, marketing analysts, consumer experts, and manufacturing personnel. The involvement of different qualifications in a design project is inevitable as each qualification provides a different dimension to the design process. However, the coordination of tasks performed by these qualifications always represents the initial challenge of any design project. In practice, a product idea may be presented to a head of a company who gets excited about it and decides to implement it; this often leads to a series of questions including where to start, how to begin a design project, and who should be in charge? For this reason, it is always important to convert the design process into a stepwise design system with well-defined inputs and measurable outputs.

An example of a design system developed by the author and has been implemented in actual design projects is illustrated in Fig. 5.2. It is called the "CMOM" system or the "concept-modeling-optimization-manufacturability". It follows the criteria of the product model mentioned earlier. The first criterion implies that a product model should reflect and resemble a well-defined design concept that is stated clearly in the problem definition and supported by creative thoughts and initial rough sketches or images of the anticipated product. Resemblance of a design concept means a product image that satisfies the shape and the purpose of the intended product. In this regard, the design conceptualization aspects discussed in Chapter 4 should represent the starting point of a design system. The second criterion of a product model is visibility and predictability. Visibility implies distinguishability and perceptibility. Predictability, on the other hand, implies expectedness with some certainty. These represent a true challenge in the design of textiles as a result of the complex nature of fibers. By comparison with other materials, fibers are solids but often act

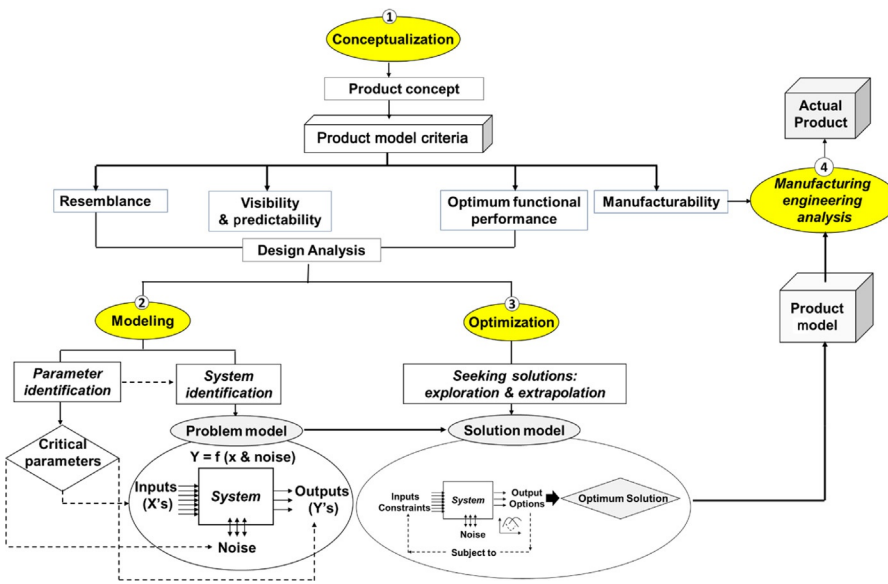


Fig. 5.2 Basic analytical steps of design analysis: the CMOM system [2].

as liquids; they enjoy high flexibility making them easily manipulatable, but this could also mean a loss of dimensional stability; they can be elastic, plastic or viscoelastic depending on external stimulus; they exhibit polymeric memory that can result in undesirable responses such as shrinkage, creep, crimp, and relaxation; they can be hydrophilic or hydrophobic; they can transform or store water by absorption or by capillary effects; they can be thermally resistant or may melt or burn easily; their behavior under static conditions can be totally different than that under dynamic conditions; their surfaces can be smooth or rough, easily abraded, or highly resistant to abrasion; they can entrap air in such a way that no other material can; they can be manipulated into porous structures or impervious structure; they can be UV sensitive; and they can be chemically sensitive or highly resistant. These are all aspects that influence visibility and predictability.

The third criterion in the "CMOM" design system is achieving optimum functional performance. This is the essence of design analysis, which is based on iterative process to reach the optimum solution of a design problem. The multiplicity of fiber attributes mentioned earlier provides ample opportunities to find many solution options for the design problem. However, the complex structures of fibrous products (e.g., fiber discrete nature, inherent variability, anisotropy, memory and hysteresis, dynamic behavior, and time-domain responses) represent true challenges in the optimization process. This means that any optimization process must be preceded by developing reliable relationships between performance characteristics and different design factors. Unfortunately, many design problems of textile products are ill defined by virtue of the complexity mentioned earlier. This is particularly true for design problems in which a trade-off must be made between two sets of contradicting functional characteristics. For example, protective clothing such as bulletproof vest, military clothing, firemen clothing, and mine worker clothing requires a trade-off between high density/heavy weight and comfort. As a result, a design model should be developed relating different attributes to the performance characteristics that can meet this trade-off.

When design problems are ill defined, two types of model should be developed: problem-focused model and solution-focused model. In other words, the design engineer should be a problem led before being a solution led. This requires a focus on modeling the problem before modeling the solution. Modeling design problems should typically begin by extensively reviewing scientific research associated with the problem. Recall in Chapter 3 that one of the key differences between scientists and engineers was that scientists spend more efforts exploring the problem than solving it. This is where the bridge between engineering and science must be established in any engineering design problem. However, scientific problem modeling is often associated with idealization of the relationships between input variables and output variables, and in many situations, linear relationships are assumed to simplify exploration of the problem model. This is where an engineering problem modeling will be required, which can typically begin with an existing scientific problem model and then be modified in view of practical constraints that are normally unseen in research laboratories.

Engineers involved in the design of textiles and fashions must learn about design cognitions. Developing problem models and solution models of engineering design has been a true challenge not only in the textile industry but also in virtually all

industries [51–53]. One way to overcome this challenge is to begin with a problem model in which one parameter at a time is considered. These are called parameter identification models. Typically, key design parameters are listed based on a brainstorming process, and each of the top-most critical parameters is handled independently. This process will yield a set of parameter identification models that the designer can use in establishing factor levels and key constraints of the design problem. At this point, the designer may proceed with optimization analysis based on parameter identification models or seek more integrated models to reach a point at which the entire product system is largely identified (i.e., quasi system identification).

When a design system is largely identified, it will become possible to perform design optimization analysis. An optimization process should ideally begin with a design-solution model derived from the problem model. This will allow exploring different internal and external aspects of a product and even extrapolate the performance of a product under additional constraints not included in the initial design system. Exploratory analysis can be carried out by evaluating the effects of input parameters on the performance of output parameters. In this regard, statistical techniques such as design of experiment and analysis of variance can be very useful.

Predictability is another key criterion as it means not only anticipating some outcomes with some degree of certainty but also, more importantly, providing opportunities to revise and control the product system so that key design principles such as simplicity, support, familiarity, encouragement, and safety can be fulfilled as discussed in Chapter 4. The common goal of an optimization analysis is to determine the maximum or minimum values of desired system parameters subject to some constraints associated with prespecified input factors or other external parameters. The success of an optimization analysis will largely depend on how well the system was identified in the modeling phase of analysis. The outcome of an optimization analysis is a design model leading to a physical product model or prototype. This model can be made in the form of an actual physical product or a virtual model using computer-aided-design software programs.

Finally, the product model should be manufacturable into an assembly in which design specifications are coordinated with manufacturing parameters to yield a final product of optimum performance. Although this criterion represents a bridging aspect between design analysis and manufacturing, it should be highly considered in the design phase so that a smooth transition from a product model to an actual product can be achieved. For instance, modeling analysis should account for noise or external parameters that may not be observed at the prototype scale but are anticipated in actual operating conditions. Similarly, optimization analysis should account for constraints anticipated during manufacturing.

5.7 Case study of CMOM design system: Design for comfort

In this section, examples of design problem models associated with textile products are presented. The focus will be on the design for comfort, which is a significant aspect bridging the design of textiles and fashions. The choice of this type of design stems

from the fact that regardless the type of clothing human wear (traditional, smart fashion, or functional clothing), comfort aspects must be satisfied; otherwise, clothing will be rejected on arrival. On the other hand, design for comfort represents one of the ultimate complexities of engineering design that has not been fully resolved despite the great progress that has been made in the field. The CMOM system design approach described earlier was implemented in a project sponsored by the National Textile Center (NTC) and Department of Commerce, in 2003. The main objective of this project was to develop a design-oriented comfort model [54]. The project was led by the author, and it involved many distinguished researchers from North Carolina State University, Georgia Tech, Auburn University, and Clemson University. This project lasted 3 years and covered numerous aspects of clothing comfort from fiber selection to the design of different types of fabrics and garments leading to many important results and patents that have been used in many design applications in the industry. In the following discussion, only an overview of the implementation process of the CMOM design system in this project will be presented without going into too much details of all aspects of the project. The discussion will involve some scientific details that readers who are not interested in this specific subject may skip and move on with the rest of the chapter.

5.7.1 Design conceptualization for comfort

Referring to the key aspects of design conceptualization in Chapter 4, any product idea must be well justified, and the design problem must be well defined. In the context of clothing comfort, product ideas typically focus on providing two types of comfort: neurophysiological comfort or thermophysiological comfort. Neurophysiological comfort (also called tactile or sensory comfort) of clothing refers to the feel of fabric against the skin and the accommodation of clothing to body movement. Thermophysiological comfort of clothing refers to the fact that clothing represents an intermediate media between the human body and the surrounding environment; as a result, it should act as an adjusting or a controlling system for the sake of accommodating the effects imposed by many thermal factors such as air temperature, radiant temperature, humidity, and air movement.

Most commercial textile products that are claimed to provide comfort are typically designed to provide thermophysiological comfort. This is because of the many relatively deterministic aspects associated with this type of comfort that can be designed in and tested in accordance to many standard procedures and specifications. These products may be designed to produce cooling or warming effects; they can also be designed to control moisture transfer from the body to the environment or vice versa. Therefore, consumer's judgment of these products can easily be realized particularly under extreme weather conditions or high physical activities associated with heating and sweating.

The design of clothing for neurophysiological comfort has traditionally been perceived as a direct consequence of the principles of making fabric and clothing. Most fibers used for clothing exhibit a high degree of flexibility; they are converted into yarns based on the principle of maintaining their flexibility (i.e., by twisting or wrapping); yarns are then converted into fabrics by interlacing or interlooping, which are

essentially flexibility-driven binding mechanisms; then, the art of making clothing preserve flexibility all the way to the end product making clothing pliable and conformable to body shape and size and at minimum obstruction to body movement. Most fibers also exhibit smooth surfaces, and when surface roughness is an issue (wool fibers scales, yarn hairiness, or fabric surface irregularities), the magic of dyeing and finishing come into play to provide smoothness and friendly touch by the fabric to the human skin.

In view of the earlier brief conceptualization of the design for clothing comfort, it would seem logical to assume that the focus of this type of design should be on the thermophysiological comfort since neurophysiological comfort can be assumed as given. This is perhaps why most design activities focus on thermophysiological comfort. The problem with this assumption stems from many important key design issues:

(a) The design for thermophysiological comfort often comes at the expense of the neurophysiological comfort. This can easily be seen in many commercial protective clothing in which humans are wearing clothing system not natural clothing.

(b) As pointed out earlier, many of the new smart fashions and functional clothing largely failed to provide the natural desirable feeling of clothing. If wearers of clothing become sensitively aware of the interaction between their bodies and skins to the clothing they wear, the neurophysiological aspect of comfort will largely be violated and will no longer be taken for granted.

(c) The awareness of neurophysiological comfort progressively increases as human activity changes from resting to walking to running and to performing high physical activities. This is perhaps the most complex aspect of design conceptualization for neurophysiological comfort. Human body reaction to movement is typically sensed by body kinesthetic senses, which reflects the awareness of our own body movements and the reaction of our limbs and muscles to movement, or what is known as muscle memory; we raise our legs as we walk; we carry things by hand all the time; and we perform functions such as typing words by fingers, all without looking at what we do. These are all internal activities that we perform on regular basis, but we are hardly amazed with how we do them. In other words, the nervous system that assists us in doing these things always manage to do them smoothly and silently. Improper design of clothing can easily come in the way of these natural activities by aggravating kinesthetic senses particularly under heavy physical activities. Clothing can also come in the way of our vestibular sense, which is the sense of balance, or our ability in sensing our movement in relation to the external world. These critical aspects simply indicate that design for neurophysiological comfort can be extremely complex since ultimately the functions of these senses must be measured for naked and clothed bodies to be able to tell the difference.

(d) The interaction between the body skin and clothing is another complex aspect in the design for neurophysiological comfort. This brings about another human sense, which is the cutaneous senses, which includes touch and everything else we feel through our skin: roughness, smoothness, temperature, texture, pressure, vibration, and pain.

(e) Many commercial textile products are known to be neurophysiologically uncomfortable, yet they have been tolerated by wearer to satisfy other preferences such as the look and appearance. For example, since the 17th century, people have been wearing neckties, which represent a stifling and oppressive item worn as decorative accessory. Although many people think of neckties as perhaps the most uncomfortable textile item ever made, many men are still willing to strangle themselves with a $200 nice-looking silk necktie. From a

design conceptualization viewpoint, it is time to start thinking about a substitution item that can satisfy both the look and the comfort criteria.

(f) The friendly relationship between fit and comfort is often abused through the design of fashionable and admittedly nice-looking tight clothing. In recent years, tight clothing has made their way to different types of traditional outfits. Many experts in the medical field have expressed their views on tight clothing based on many cases that they have witnessed in which tight clothing was health hazardous, and few scientific studies were published on the effects of tight clothing on the human body [55–58]. Dr. Nicholas Morrissey, vascular surgeon with New York-Presbyterian Hospital/Columbia University Medical Center, indicated that many of his patients who wear skinny jeans complained about numbness going down one's thigh known as meralgia paresthetica, which is a result of a sensory nerve that comes from one's pelvis that provides sensation to parts of the thigh. He further elaborated that the condition itself isn't dangerous, but if one keeps having repeat episodes, it can cause permanent damage. Dr. John Michael Li, a neurologist at Rush University Medical Center in Chicago, indicated that many patients suffer from what he described as "tight pants syndrome," marked by abdominal discomfort, heartburn, and belching from wearing those skin-tight slacks. Normally, the pants are 3 in. too small for the person's waist. Other studies indicated the effect of tight clothing on compromising blood flow to the human brain. The seriousness of these points stems from the fact that many people see clothing and fashion much more as a reflection of their appearance, style, and look, but they also have a blind trust and confidence that clothing will do no harm; even when they feel it, they tend to tolerate it. This places a huge responsibility on the designer of clothing to provide neurophysiological comfort along with fashion even when a trade-off exists.

As indicated earlier, a critical initial element in the CMOM design system is to think of the anticipated product model criteria before proceeding with design analysis. These criteria include resemblance of a design concept, visibility and predictability, optimum functional performance, and manufacturability. In the design for comfort, a product model should meet the requirements of the intended design concept without violation of other concepts. As pointed out earlier, a product model intended for thermophysiological comfort should not neglect the neurophysiological aspects. When this occurs, the product model will be one-dimensional, and it will likely fail to resemble the holistic design concept of the product.

The visibility and predictability criterion of a product model represents a critical aspect in the design of clothing for comfort. As indicated earlier, visibility means perceptibility and distinguishability. It implies external factors associated with appearance such as clothing style, fit, and color. These are largely judged by the buyer of the product at the time of purchase. It also implies internal factors stemming from the sensation of comfort whether it is neurophysiological or thermophysiological. These are ultimately judged by the consumer of the product after wearing the product for some time. This is where predictability comes into play to set consumer's expectation of the product's performance. In design applications for thermophysiological comfort, predictability can be established with some level of certainty through many objective testing methods of the product model. As will be discussed shortly, design models for thermophysiological comfort are largely system identified. In design applications for neurophysiological comfort, predictability represents a challenge resulting

from converting different related attributes to performance functions. This point will be discussed shortly in the context of design models for neurophysiological comfort.

The third criterion of product model in the CMOM design system is optimal function performance. Unlike many of the functional performance characteristics that can be optimized using straightforward design analysis, optimization of clothing comfort characteristics is extremely difficult, and it is more challenging in the design for neurophysiological comfort than in the design for thermophysiological comfort.

One of the major issues facing setting reliable criteria of product models for comfort is the psychological effect. In both categories of comfort, researchers used the term "physiological" to imply the normal functions of living organisms and their parts or the way in which a living organism or bodily part functions. These are the biological effects associated with comfort. It is our opinion that this term alone does not fully reflect the comfort aspect, and it can be misleading in the process of design of clothing for comfort. A better term should be based on physiological psychology, which is a subdivision of behavior neuroscience or biological psychology that studies the neural mechanisms of perception and behavior through direct manipulation of the brains [59]. In other words, we should use terms such as "thermophysiopsychological comfort" or "neurophysiopsychological comfort" to describe the two categories of comfort. Admittedly, this will make the design process for comfort much more complicated, but it is inevitable to link psychology and physiology in conceptualizing the design of clothing for human comfort. In the NTC comfort project, fuzzy logic analysis was used to develop membership functions on the awareness aspect of clothing comfort [60–64].

5.7.2 Design problem model for neurophysiological comfort

The effects of fabric and clothing on neurophysiological comfort have been the subjects of scientific research starting with Peirce's work [8] in 1930. Since this time, hundreds of studies were devoted to exploring the phenomenon of tactile comfort in terms of different fibers and fabric attributes [65–78]. In the NTC project, the design problem model developed for clothing neurophysiological (tactile) comfort was based on the definition that "clothing comfort is the state at which the fabric in contact with the human body has a minimum mechanical interaction with the human skin and can optimally accommodate human body movement." This definition opens the door for further exploration of human kinesthetic, vestibular, and cutaneous senses, particularly in applications such as medical textiles and protective clothing. To account for both fabric/skin surface interaction and the biomechanics effects due to the pressure exerted by the fabric on the human body or vice versa, the common response variable used was the ratio between the true area of fabric/skin contact and the corresponding apparent area. This was defined as the "A-ratio." This ratio is highly sensitive to both surface interaction and mechanical interaction. Even at resting position, the human body is never motionless. The apparent area of contact can either be measured or estimated from Du Bois equation. Under any circumstances, the true area of contact between the fabric surface and the solid or skin surface will be much smaller

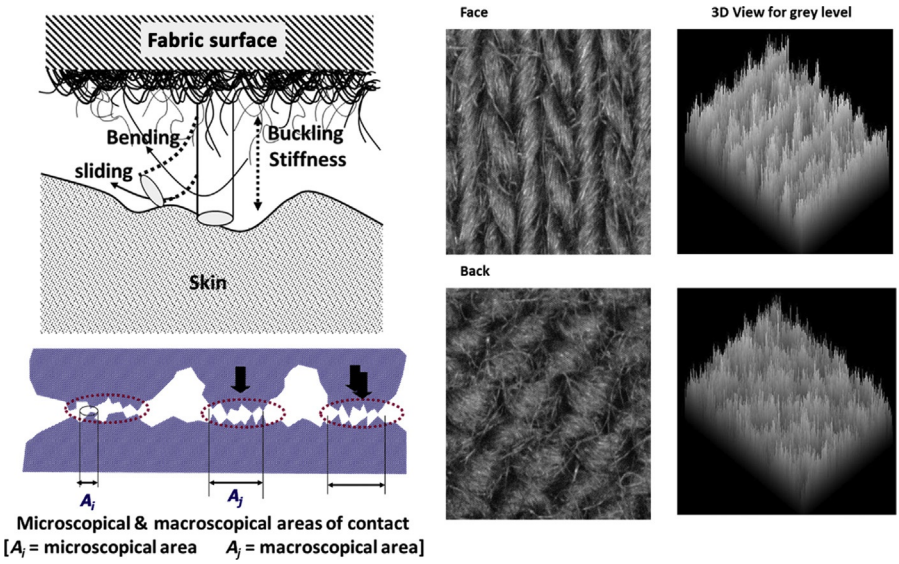


Fig. 5.3 Examples of structural- and design-related parameters revealed in the area-ratio model [67–70].

than the apparent area of contact. The true area of contact consists of two types of contacting asperities (see Fig. 5.3).

Macroscopic asperities: These are created by gross gaps in the fabric as a result of the expected fabric surface texture (crossover points, loops, piles of fibers projecting from the yarn or the fabric surface, yarn irregularities, and some special surface finish—chemical or mechanical). The area of contact in this case, which is termed *macroscopic contact area*, is determined by the sum of the macroscopic asperities or the sum of the gross tips of the contacting peaks that are existing on the surface of the bodies.

Microscopic asperities: These represent much smaller contacting points that are located within the macroscopic asperities. The area of contact in this case, termed microscopic contact area, is determined by the sum of the areas of the tiny tips of the contacting asperities (peaks) that are existing on the surface of the bodies.

The general equation of A-ratio was as follows [60]:

$$\frac{A_t}{A_a} = (C_M)^{\frac{1}{1-\gamma}} K^{-\left(\frac{\gamma}{1-\gamma}\right)} M_a P^{\left(\frac{\gamma}{1-\gamma}\right)}$$

or

$$\frac{A_t}{A_a} = (C_M)^{\frac{\alpha+1}{\alpha}} K^{-\frac{1}{\alpha}} M_a P^{\frac{1}{\alpha}}$$

where A_t is the true area of contact, A_a is the apparent area of contact, C_M is a constant dependent on the load distribution on the area of contact (approaches unity for most distributions), K is an index of surface resilience ($N/m^{2/\gamma}$), P is the lateral pressure on the true area of contact in Pa (or N/m^2), M_a is the number of asperities per unit apparent area, α is a constant that lies between 0 for purely plastic behavior and 1.0 for purely elastic behavior, and $\gamma = 1/(1+\alpha)$.

The general model earlier represented the basic problem-oriented model for neurophysiological (tactile) comfort. The mathematical complexity of the model is attributed to the complex nature of fabric/body interaction. In simple terms, the model indicates that without understanding the pressure distribution between clothing and the human body, any effort to design clothing for tactile comfort will be incomplete. Understanding the load distribution (C_M index) between the fabric and human body will allow design of clothing in which high-pressure areas in the human body are accommodated by special fabric design in which key parameters such as fabric thickness, fabric density (threads/inch in vertical and horizontal directions), yarn structure (fine vs. coarse), and fiber type (bending and tensile modulus) are carefully selected to accommodate the human body at rest and in motion.

Following this study, many research efforts were made to analyze load distributions between clothing and the human body [73–76]. For example, one study [73] aimed at using finite element analysis to simulate the large deformation behavior of garments and their clothing pressure distribution on the human body. In this study, the contact pressure distribution on the human body caused by clothing was predicted leading to a fully automatic and seamless simulation of the clothing process for pantyhose and T-shirts. In another study [74], clothing pressure was evaluated by wearing clothes on a human body or a dummy and measuring the pressure using pressure sensors. In this study, a technique for predicting clothing pressure by the finite element method was developed using the experimentally obtained tensile properties of knitted fabrics. A girdle was sewn using the chosen knitted fabric, and it was verified that the girdle can provide a comfortable sensation because it produces the appropriate pressure. In another study, the same researchers [75] developed a "hyperelastic shell with a truss model," which expresses anisotropy and nonlinearity as a knitted fabric extension characteristic and introduced an application example using pants. The clothing pressure values predicted using their computer simulation analysis proved to be very close to the actually measured values. Another study [76] performed simulation analysis of clothing pressure change in T-shirts during jogging. This analysis aimed at developing stabilized electrocardiographic measurement for a person during exercise.

The area-ratio model also accounts for fabric roughness, via M_a, which is the number of asperities per unit apparent area. This is one of the most critical aspects of fabric/skin interaction. In a design-solution model, the number of asperities per unit area primarily indicates fabric surface roughness, which can be reflected in many structural factors including clothing seam structure, yarn structure (twist and count), yarn irregularities particularly thickness variation and hairiness, and fiber stiffness and fineness. The complexity of fabric surface roughness and its effects on the human skin has been investigated in many scientific studies both in dry and wet conditions [77–79]. The area-ratio model addressed fabric roughness at both the macroscopic and microscopic scale. It also eluded to the point that the sensation of this roughness is

once again dependent on the pressure exerted by clothing against the human body. The definition of surface roughness in the area-ratio model is very unique as it defines a smooth fabric surface as the surface that consists of numerous fibers exhibiting high flexibility. From a design perspective, this translates primarily to very fine fibers such as microdenier fibers. Furthermore, mechanical and chemical finishing of fabric can significantly alter surface roughness and fabric hand [80].

Surface resilience is another critical aspect of the area-ratio model represented by the K-index ($N/m^{2/\gamma}$). In classic design, resilience of material is defined as the amount of energy that the material can absorb and still return to its original state. It can be expressed under various modes of deformation. In the area-ratio model, the type of resilience considered is that under lateral pressure or when fabric is under compression. This factor is directly related to tactile sensation of fabric. Given the fact that wearing clothing involves compressional stress, which is low in some areas of the human body and high in other areas, makes classic resilience analysis limited in characterizing human responses under compression. This is due to the fact that the compressional behavior of clothing against the human body can undergo different modes of deformation from purely elastic to viscoelastic deformation under high physical activities. From a design perspective, this translates to key design parameters such as fabric softness and fullness determined by fabric thickness, type of weave or knitted design, yarn structure, and fiber fineness and buckling rigidity [81].

The discussion earlier clearly indicates that design for clothing neurophysiological (tactile) comfort is not a trivial task. Indeed, it is one of the most complex types of engineering design that can be undertaken. The challenge associated with the transition from a problem-oriented (exploratory) model to a solution-oriented model has been one of the reasons why we do not see many clothing developed and advertised as being fully tactile comfortable. It takes another effort of design analysis to make such transition. This can be achieved using extensive trial-and-error experimentation associated with empirical models and extensive testing of different comfort-related parameters.

5.7.3 Design problem model for thermophysiological comfort

The need for problem-oriented models in the design of clothing for thermophysiological comfort stems from the fact that the human body is highly sensitive to various external conditions imposed by seasonal changes including changes in ambient temperature, vapor pressure, air velocity, and clothing insulation. The human body is also never motionless and always produces heat that is transformed to the surrounding environment. When extreme weather conditions and high physical activities are added to the equation, exploring all these factors in a problem-oriented model becomes a critical aspect in the design for thermally friendly clothing.

Thermophysiological comfort deals with four basic environmental parameters that affect human response to thermal environments: air temperature, radiant temperature, humidity, and air movement. As an intermediate portable environment between the human skin and the surrounding media, clothing may influence these basic environmental parameters in a direct or an indirect fashion. The anticipated role of fabric in this regard is to provide an optimum accommodation to changes in the surrounding media. The different parameters of thermophysiological comfort are well defined

by the general heat balance equation of the human body reported in ASHRAE Standards [82, 83]. These standards indicate that the main components of heat balance are the heat production within the body, the heat loss at the skin, and the heat loss due to respiration. The primary role of clothing in the process of heat balance is to act as an adjusting media between the human body and its environment. The nature of interaction between this media and the human skin represents a vital factor in understanding the common thermophysiological effects such as thermal insulation, moisture, and vapor transfer through clothing, different modes of heat exchange with clothing (conduction, convection, radiation, evaporation, and condensation), and air penetration.

In the context of design, a body-clothing system may be modeled based on many mechanisms such as heat transfer through the human body and clothing systems, moisture transport, pumping effects, breathability, ventilation, and interaction with wearer's activity [84–87]. Typically, scientists begin modeling this system by assuming dry clothing and utilize basic equations of heat transfer. In this case, the focus of modeling is on the heat transfer mechanism as shown in Fig. 5.4. This requires consideration of many parameters including the metabolic heat produced by the body, heat transfer to the skin, changes in skin temperature, and sweat and the intrinsic clothing insulation. The latter parameter may be modeled by another set of inputs including the body surface area, skin-clothing temperature gradient, and clothing thermal conductivity.

Scientific modeling may also account for different forms of heat transfer in the body-clothing system. These include conduction, convection, and radiation. The final model will then accommodate basic heat transfer equations such as the thermal resistance of the environment for a nude body (I_a), the thermal resistance of the environment for a clothed body (I_{ac}), and the dry heat loss from the skin (DHL). Scientists may then proceed with the analysis considering the ratio of the clothed

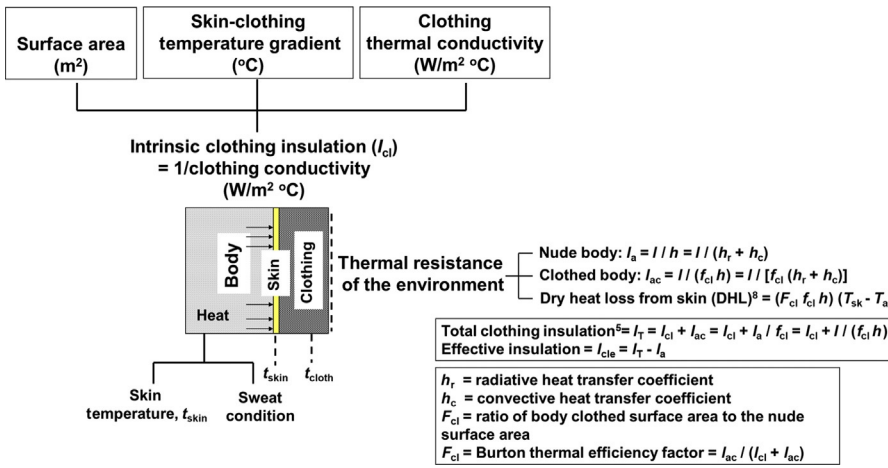


Fig. 5.4 Design problem model for thermophysiological comfort [85–87].

surface area of the body to the nude surface area of the body, f_{cl}, based on the hypothesis that the surface area for heat transfer of a clothed body will be increased with the increase in the thickness of the clothing layer. However, measurements of this factor will be extremely difficult in a typical laboratory environment. As a result, this factor will be roughly estimated or obtained from photographic techniques, anthropometric scanners, or copper manikin measures. The total insulation associated with the simple body-clothing system model is a function of the intrinsic clothing insulation, l_{cl}, and the thermal insulation of the environment for a clothed body, l_{ac}. This parameter must be adjusted for the effect of thermal insulation of the environment for a nude body, l_a, leading to the more convenient term, l_{cle}, which is the effective clothing insulation.

The design process of clothing for thermophysiological comfort has made significant progress in the last 40 years. In Chapter 12, we will elaborate further on some of these developments.

5.8 Understanding the difference between basic attributes and performance characteristics

As indicated in Chapter 3, determining and defining the performance characteristics of a product is a critical phase of product development (see Fig. 3.1, Chapter 3). Any product should be associated with performance characteristics that describe its intended function(s) and reflect its expectation(s) by the users of the product. For example, the primary performance characteristic of a raincoat is waterproof capability, and that of a firemen uniform is flame retardant. These characteristics are highly anticipated and naturally expected by the users of these products, and any deficiency in them will be met by dissatisfaction or a total rejection of the product. As will be discussed in detail in Chapter 12, one of the primary challenges in the design of textile products is incorporating performance characteristics in the design of textiles. The current industry's approach is typically a quality assurance approach. For example, hospitals and hotels may specify durability as the key performance characteristic of bedsheets due to their frequent use and the need for daily washing and tumble drying using large commercial laundry machines. In these situations, the traditional approach of the textile industry is to simulate durability in reference to consumer's need by performing washing and dry test for many cycles and inspect progressive deterioration in physical properties or significant changes in dimensional characteristics. This approach is commonly used in many other industries for testing potential failure of products after repeated use. It is used in these industries not only as a quality control tool but also as a design validation tool. A repeated washing and drying test for measuring durability will simply reflect the status and the behavior of the bedsheet under rigorous applications, but it will not necessarily close the design loop. In other words, the true benefits of the result of this type of testing should not be to pass or fail to pass a product but rather to determine the key attributes contributing to the performance characteristic under consideration. From a design perspective, the term durability per se is not a measurable characteristic, and it could mean different things; a product lasting 100 washing and drying cycles versus another lasting half this number of cycles may mean better raw materials, appropriate

fiber blend, firmer structural integrity, and better basic attributes that must be identified and measured so that a future product can perform even better; this is the essence of engineering design. Durability is only one example of numerous performance characteristics of textile products that are not directly measured and cannot be quantitatively described.

A performance characteristic is hardly a direct attribute that can be measured and imbedded in a product in a systematic fashion to make the product perform according to its expectation. Instead, it is often a function of appropriate structural assembly leading to a combination of different attributes that collectively result in meeting the required performance. Durability as a design criterion represents a familiar example to most engineers, and it is considered in virtually all products. Other performance characteristics that are unique to textile products including style and fitability are more difficult to define and quantify. As a result, engineering designs of products that can meet these characteristics require appropriate problem models in which all potential parameters contributing to the performance characteristics are listed, existing scientific models are considered, and related attributes are tested. In Chapter 12, this subject will be discussed in view of the so-called performance–attribute diagram, shown in Fig. 5.5. For most fibrous products, these attributes are those of the different

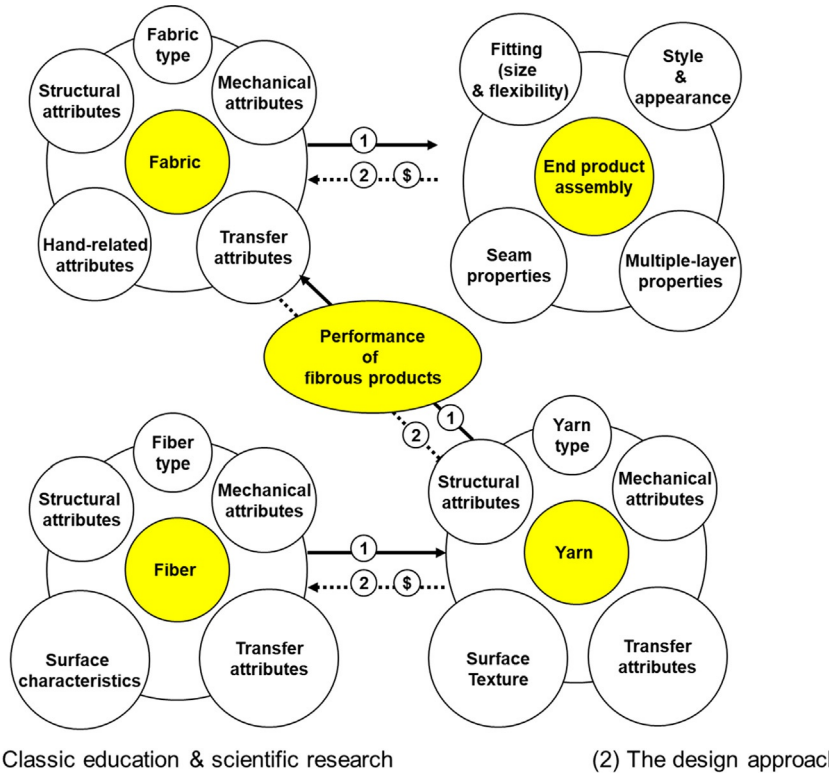


Fig. 5.5 Performance-attribute diagram [2].

components comprising the product, namely, fibers, yarns, fabric, and product assemblies. Note that material type (e.g., fiber type, yarn type, and fabric type) is a common key component in the performance–attribute diagram. In classic textile engineering education, the learning process begins with courses on fiber characteristics and then proceeds in a linear sequence to yarn courses and then to fabric courses, with each course being a prerequisite of the next one. This approach follows closely the arrowed solid lines in Fig. 5.5. The legitimacy of this approach stems from the fact that at this stage of learning, a pyramidal sequential approach is useful to provide students with the necessary knowledge base. In product development, the approach is quite different as the starting point of gathering information and establishing a knowledge base is at the end-product assembly. A backward projection approach is then taken following the arrowed dotted lines in Fig. 5.5 to develop the end product through various manipulations of fabric construction, yarn structure, and fiber parameters. In some situations, a design engineer may break the backward projection sequence by going straight to fiber parameters as they may represent the most critical factors in determining product performance. In this regard, modeling performance characteristics in terms of these various contributing elements can greatly assist in determining the most significant factors influencing product performance. The backward projection approach should also be associated with cost analysis starting with the anticipated cost of the end product that can justify its value in the market place and then breaking down this cost into subsequent conversion costs.

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Engineering design for sustainability in the textile and garment industry

6

6.1 Introduction

Key aspects such as functional characteristics, aesthetics, cost, safety, and manufacturability have always been an integral part of engineering design. These aspects have been met by placing engineering in the interface between science and technology as described by the engineering operating system, EOS, discussed in Chapter 4. Quantitative methods of engineering design begin by adopting problem models that are initially derived from scientific research but have business merits and market potentials. These models are then converted into solution models in which functional characteristics are optimized subject to many constraints including resources available, cost, and safety measures. The outcome of optimization analysis is a product model or a prototype that simulates the final physical product. At this point, technology takes over and proceeds with the analysis of large-scale product manufacturability. These points were illustrated in Chapter 5 using the "concept-modeling-optimization-manufacturability" system, CMOM.

Over the years, engineering design has evolved in accordance to the evolutionary changes in marketing theory. In Chapter 2, five marketing phases were described: the customization era, the production-focus era, the product-focus era, the consumer-focus era, and societal marketing era. In the customization era, products were tailored in a personalized fashion, and it was designed to last a lifetime. The production-focus era was sparked by the Industrial Revolution, and it meant product design that can satisfy the widest range of consumers through key design features including diversity, quality, and consistency. The product-focus era was all about product uniqueness, added-value, and special design features that can attract more potential users. The consumer era was more of a return to the customization era but through mass customization, and it also required special design criteria in which factors associated with consumer's inputs and shorter time to market or quick response were considered. Finally, the societal marketing era came with new consumer demands due to the rise of globalization and the availability of immense information via the internet and social media that meant product designs based on competitive factors and international trade and safety regulations.

In the 21st century, the global market is likely to enter what we call the "societal approved" era. This will be the era in which society as a whole will have a higher voice in determining what constitutes an acceptable product than an individual or a segment of consumers. This era will be a result of the increasing demand to reduce environmental impacts and improve human well-being. This movement actually began in

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the middle of the 20th century, but it has been materialized into products and services since the beginning of the 21st century. Now, the most common term used around the world is "sustainable development" and the need for sustainable products. It has been a work in progress to reach this point starting in 1970 with the establishment of the US Environmental Protection Agency (EPA) to ensure environmental protection. Around the same time, a major US political debate about environment yielded the so-called IPAT equation describing the major factors influencing environmental impact. Since this time, environmental regulations have evolved into constitutional laws, legislations, and international agreements. In the 1980s, the famous Brundtland Commission was established by the UN General Assembly, and the term "sustainability" was introduced for the first time and defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." By the beginning of the 21st century, consumer's demand for more sustainable products has reached a point that now, all business organizations must take into consideration the sustainability aspect in the development of all products and services.

In the context of product design, sustainability adds more constraints that have not been considered in the past. Now, a selection of raw material in an engineering design must account for the source of material, how it was produced, and from what resources. The make of a product must account for the ecological impact of the process utilized to manufacture it. This means that factors such as energy consumption, water waste, and air or water pollution must represent integral aspects of any design project. Products must also be designed to last long and to be reused or recycled upon competition of its normal service life. This will mean a transition from a design by assembling to design by disassembling as well. Product design in the "societal approved" era will be based on circular economy and life-cycle analysis. These aspects are discussed in this chapter.

6.2 Evolutionary aspects of the concept of sustainability

As indicated in Chapter 2, the Industrial Revolution had led to a significant transition from the customization era to the production-focus era in which the common assumption was that demand will always exceed supply and supply creates its own demand. This was also prompted by a significant increase in the world population reaching 1.6 billion people by the end of the 19th century. The industrial revolution also marked a revolutionary change in earth's ecology and humans' relationship with their environment. Production capacity was exponentially increased to meet all basic human needs including food, medicine, housing, and clothing. Products were produced much faster and of better performance. However, these benefits were achieved at the expense of the impact of technology on natural resources, public health, energy usage, water consumption, pollution, and sanitation.

By the mid-20th century, the world was entering a race in which population growth continued to rise exponentially from 1.6 billion people in 1900 to about 6 billion people in 2000 leading to exponential requirements for resources, energy, food, housing and land, and exponential increase in waste by-products. Recall that one of the

driving forces of the Industrial Revolution was the abundant fossil fuel coal, which forever changed the concept of energy utilization. Undoubtedly, the use of fossil fuel represented a revolutionary industrial development, but it was also at extraordinary costs to our environment and ultimately to the health of all living things. In 1949, the first alarming sign regarding this issue came from M. King Hubbert [1,2], an American geophysicist, who predicted that the fossil fuel era would be very short-lived and that other energy sources would need to be relied upon. In 1962, another early warning of the impact of industrial development on environment and human well-being was expressed in a book published by Rachel Carson titled *Silent Spring*. In this book [3], Rachel warned of the dangers to all-natural systems from the misuse of chemical pesticides such as DDT and questioned the scope and direction of modern science. Before her death in 1964, she was able to make the general public aware of the cause and effect of human outgrowth from the Industrial Revolution by taking on the powerful and robust chemical industry raising important questions about human's impact on nature. This was the first time the public and industry began to grasp the concept of sustainable production and development.

By the early 1970s, awareness of the impact of industrial development on environment and human well-being was at a point that had attracted some prominent US politicians. In 1971, the so-called IPAT equation was the center of attention by many environmentalists around the world. This was perhaps the first equation in history that had come out of a political debate. The three champions of this debate were Barry Commoner (1917–2012), an American cellular biologist and politician, known for his running as the Citizens Party candidate in the 1980 US presidential election; John Paul Holdren, professor of environmental policy, who served as the senior advisor to president Barack Obama on science and technology issues; and Paul Ehrlich an American biologist, best known for his famous 1968 book *The Population Bomb*. The debate was about environmental impact; Commoner argued that environmental impacts in the United States were caused primarily by changes in its production technology following World War II that led to deteriorating environmental conditions. Ehrlich and Holdren argued that technology alone could not be blamed and other factors such as population growth and the increasing consumption of goods also contribute to environmental deterioration. The positive outcome of this debate was a conceptual equation, known now as the IPAT equation developed jointly in 1971, which was in the following form [4,5]:

$$I = P \times A \times T$$

This equation assumes that the environmental impact (I) was primarily a result of three basic parameters: the size of the human population (P); affluence (A), or the level of consumption by the population; and technology (T), or the processes used to obtain resources and transform them into useful goods and wastes. An increase in just one of these parameters, therefore, increases our environmental impact.

As indicated earlier, the IPAT equation was not mathematically or empirically driven; it was a simple visual expression derived by intuitive narrative that reflected a political vision of the cause of environmental deterioration at a time the world

population was only 3.8 billion. Furthermore, the IPAT equation was not generated from a specific approach of inductive reasoning, and therefore, it will be very difficult to use deductive reasoning to verify or test its validity. Indeed, the dependent variable in the IPAT equation, which is the environmental impact, I, would require many indicators to measure [6] such as air quality, land loss, water quality, forests, seas, animals, and all other living and nonliving elements of this planet Earth. When environmental impact is viewed in terms of the bigger concept of sustainability, key indicators will include GDP per capita, fuel consumption, total fertility rate, water supply, sanitation, and electricity. In addition, indicators related to technology will include waste disposal, air pollution, gender issues relating to environment, corruption, democracy, etc.

It took 10 years after the development of the IPAT equation and 20 years after Rachel Carson alarming study for the world to initiate the term "sustainability" to describe ecological impacts. This time, another great woman by the name Gro Harlem Brundtland, the former Prime Minister of Norway, became recognized worldwide for her championing of the principle of sustainable development as the chair of the Brundtland Commission established by the UN General Assembly in the early 1980s. Brundtland had a strong background in science and public health and her leadership role in the commission that carried her name was very effective. The report published by this Commission in 1987 defined sustainable development as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The report specified five challenges facing sustainability development [7,8]: (a) population and human resources, (b) food security, (c) species and ecosystems, (d) energy, and (e) industry and urbanization.

In the context of sustainability, combining the Brundtland Commission report and the concepts derived from the IPAT equation clearly indicates that the meaning of environment today encompasses much more than climates and earth aspects. Environment now implies the status of human well-being on earth, and this is what sustainability truly means. The need for sustainable environment is not only restricted to underdeveloping countries suffering from high fertility rates, high illiteracy, poor education, poor health awareness, and high population growth rates but also very applicable to rich countries that consume huge amounts of resources leading to undesirable changes in the ecological footprint and biocapacity.

The Brundtland Commission was apparently concerned about the fact that the world population has exploded in the 20th century by jumping from 1.6 billion to over 6 billion. In 2018, the world population was about 7.7 billion, and it looks like the 21st century will have another exponential increase reaching perhaps more than 10 billion by 2100. It is true that the average rate of world population growth has significantly dropped to below 1.3% since the beginning of the 21st century, but the world in 2018 reached a density of more than 50 persons per square kilometer compared with 33 persons per square kilometer at the time the Brundtland Commission report was published, and it was only 17 people per square kilometer in 1950. Furthermore, the world urban population in 2018 has doubled since the Brundtland Commission report; it reached 4.3 billion people (55% of the world population) in 2018 compared with 2.1 billion people (42%) in 1987, and it was only 0.77 billion people in 1950.

6.3 Ecological footprint indicators

Following the development of the IPAT equation and the outcomes of Brundtland Commission report, many scientists began extensive studies on defining environmental impacts using many ecological footprint indicators. These include the following:

1. The eco-footprint for production and consumption and biocapacity
2. Carbon footprint
3. Water footprint

In the following sections, these indicators will be defined and briefly discussed.

6.3.1 Eco-footprint for production and consumption and biocapacity

The most common universal parameters of sustainability are the ecological footprint and the biocapacity. The principles underlying these two parameters stem from the fact that human activities consume resources and produce waste and nature needs to have the capacity to meet these demands. The concept of ecological footprint was pioneered by William Rees [9], professor at University of British Columbia, in Vancouver, Canada, in 1992. It is a measure of human demand on nature or on the Earth's ecosystems. Consumer's needs such as food, energy, transportation, goods, and services all contribute to our ecological footprint. As a result, the ecological footprint can be used as a standardized measure of demand for natural capital that may be contrasted with the planet's ecological capacity to regenerate [10]. It represents the amount of biologically productive land and sea area necessary to supply the resources a human population consumes and to mitigate associated waste. Using this assessment, it is possible to estimate how much of the Earth (or how many planet Earths) it would take to support humanity if everybody followed a given lifestyle. The land required to meet ecological footprint is expressed by the so-called global hectares (GHA). Global hectares per person refers to the amount of production and waste assimilation per person on the planet. Footprint values can also be categorized for carbon, food, housing, and goods and services as well as the total footprint number of Earths needed to sustain the world's population at that level of consumption. As a result, ecological footprint analysis can also be applied to many activities such as the manufacturing of clothing, the consumption and waste of textile products, the energy saved by wearing certain clothing, the reduction in water consumption, and carbon dioxide emission resulting from the choice of certain fiber. The key, however, is the conversion of resources into a normalized measure of land area or GHA.

Despite the wide universal recognition of ecological footprint and the use of its calculated values, there have been differences in the methodology used by various ecological footprint studies. Agenda 21 (Chapter 40) of the 1992 United Nations Conference on Environment and Development in Rio [11] called for improved quality and availability of sustainability data for decision making. Some of the holding aspects in reaching universally standard measures include the accounting for sea area,

the inclusion of fossil fuels, the accounting for nuclear power, data sources, area distribution and categorization (e.g., agricultural land versus deserts), etc. The need for relevant and reliable data to measure sustainability resulted in the development of many indicators with the intent of driving policy and assessing progress toward sustainability. Fortunately, methods of calculation have largely been converging in recent years leading to more reliable footprint standards [9–13]. Ultimately, a reliable measure of the ecological footprint should provide an integrated, multiscale approach to tracking the use and overuse of natural resources and the consequent impacts on ecosystems and biodiversity.

The underlying calculations of the ecological footprint (EF) apply sustainability core principles to derive the amount of mutually exclusive bioproductive area on the planet appropriated by human activities. Human-harvest or waste-production flow is quantified in mass per time and translated into global hectares through the following equation [13]:

$$EF_p = EF_p = \frac{P}{Y_w} \times EQF$$

where

EF_p is eco-footprint for production,
P is the production (or harvest) in tons per year,
Y_w is the world-average yield in tons per hectare, per year,
EQF is the equivalence factor.

For each land-use type, the EQF is the ratio of a given land type's average global productivity divided by the average global productivity of the entire planet's productive surfaces. EQF makes it possible to compare the land used for a given product category with the average global bioproductive surface area, which may be of higher or lower average productivity [14]. For each country, the ecological footprint of production (EFp) of a single footprint category is calculated by adding all products of that footprint category (such as rice, wheat, and corn for cropland). The total EFp of a country is the sum of the ecological footprint of all product categories combined.

The ecological footprint of consumption for a country is estimated by calculating the ecological footprint of all that is produced within a country, then adding the ecological footprint embodied in imports, and subtracting the ecological footprint embodied in exports:

$$EF_{Consumption} = EFP + EFI - EFE$$

where

EFP is the is the ecological footprint of production,
EFI is the ecological footprint of imports, and
EFE is the ecological footprint of exports.

Biocapacity can be measured in global hectares at any scale, from a single farm to the entire planet. The following formula details how biocapacity is calculated at the national level for each biocapacity land-use category:

$$Biocapacity = A_n \times \frac{Y_n}{Y_w} \times EQF$$

where A_n is the area in country "n" for this land-use category in hectares and Y_n is the national average yield for this land-use category in tons per hectare and year.

The equations earlier indicate that for the world to achieve sustainable human population, it will be necessary that biocapacity is higher or equal than ecological footprint. According to the United Nation, the world-average ecological footprint in 2012 was 2.84 global hectares per person, and the world-average biocapacity was 1.73 global hectares (GHA) per person; this had resulted in a global ecological deficit of 1.1 global hectares per person. In the United States, ecological footprint and biocapacity were crossed in the late 1960s, and they have continued in their directions ever since.

6.3.2 The carbon footprint

Another key term used in sustainability analysis, which is related to the ecological footprint, is the so-called carbon footprint. This term is widely used in manufacturing and production of commodities and goods to indicate the seriousness of the impact of these processes in association with gaseous emissions. Carbon footprint is one of those terms that a vast majority of people use on daily basis without consensus on how to measure or quantify. The common baseline is that the carbon footprint stands for a certain amount of gaseous emissions that are relevant to climate change and associated with production or consumption activities [15]. The term carbon here implies the emission of carbon dioxide CO_2, but it can also mean other greenhouse gas emissions such as methane or noncarbon substances such as N_2O. Another issue with carbon footprint is whether it should reflect all life-cycle impacts of goods and services used and if so, where should the boundary be drawn and how can these impacts be quantified? Furthermore, the term footprint is analogous to the term ecological footprint, except for the fact that it is not directly measured in area or hectare; instead, it is measured in mass units (kilogram or ton per person or activity). The Global Footprint Network (https://www.footprintnetwork.org/), an organization that compiles "National Footprint Accounts" on an annual basis, sees carbon footprint as a part of the ecological footprint. Carbon footprint is interpreted as a synonym for "fossil fuel footprint" or the demand on "CO_2 area." In this regard, a demand on "CO_2 land" is defined by the demand on biocapacity required to sequester (through photosynthesis) the carbon dioxide (CO_2) emission from fossil fuel combustion. The most inclusive definition of carbon footprint today is the one suggested by Wright, Kemp, and Williams in their 2011 article [16], which is "a measure of the total amount of carbon dioxide (CO2) and methane (CH4) emissions of a defined population, system or activity, considering all relevant sources, sinks, and storage within the spatial and temporal boundary of the population, system, or activity of interest. This is calculated as carbon dioxide equivalent using the relevant 100-year global warming potential (GWP100).

Carbon footprint has been a part of ecological global awareness accompanied by continuous efforts to reduce it worldwide. Goal 9 of the United Nations 2018 report on Sustainable Development Goals [17] states, "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation." Under this goal, it was also stated that "*Globally, the carbon intensity decreased by about 19 per cent from 2000 to 2015—from 0.38 to 0.31 kilograms of carbon dioxide per dollar of value added*."

6.3.3 The water footprint

Water foot print is another serious indicator of sustainability that was suggested by Dutch professor Arjen Hoekstra in 2002. It is defined as the total fresh water used by a person, community, company, or country to produce the goods and services consumed [18,19]. The most elaborate publications on how to estimate water footprints are a 2004 report on the Water footprint of nations from UNESCO-IHE [20,21]. More recent publications [22,23] also discussed detailed analyses of water footprint in different applications. The water footprint is an innovative concept to analyze water consumption and pollution along supply chains, assess the sustainability of water use, and explore where and how water use can best be reduced.

The use of the water footprint adds a new dimension to the sustainability integrated concept. It may be perceived as an analogue to the ecological and the carbon footprint but indicates water use instead of land or fossil energy use. According to Hoekstra [24], the water footprint of a product is the volume of freshwater used to produce the product, measured over the various steps of the production chain. Water use is measured in terms of water volumes consumed or polluted. Water consumption refers to water evaporated or incorporated into a product. The water footprint is a geographically explicit indicator that shows not only volumes of water use and pollution but also the locations. Hoekstra added that a water footprint generally breaks down into three components: the blue, green, and gray water footprint. The blue water footprint is the volume of freshwater that is evaporated from the global blue water resources (surface and ground water). The green water footprint is the volume of water evaporated from the global green water resources (rainwater stored in the soil). The gray water footprint is the volume of polluted water, which is quantified as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards.

Sources of water footprint abuses can be rooted to everything in our life from personal use to manufacturing use. According to the US Environmental Protection Agency (EPA, https://www.epa.gov/watersense/how-we-use-water):

> *The Earth might seem like it has abundant water, but in fact less than 1% is available for human use. The rest is either salt water found in oceans, fresh water frozen in the polar ice caps, or too inaccessible for practical usage. While population and demand on freshwater resources are increasing, supply will always remain constant. And although it's true that the water cycle continuously returns water to Earth, it is not always returned to the same place, or in the same quantity and quality.*

The point of the earlier statement is that the world must determine water footprint between-country equity and generational equity if it is to survive the next 50 years. While some countries suffer a great shortage of clean water, the average American family uses more than 300 gal of water per day at home, and roughly 70% of this use occurs indoors. These problems will be resolved not only by changing people habits and daily use of water but also by substantially changing our design concepts of homes and infrastructure. Manufacturing and production use of water must also change through new design conceptualization of processes and product performance characteristics, particularly in relation to maintenance of products, which utilizes a significant percentage of clean water.

According to United Nations 2018 report on Sustainable Development [17], "water scarcity, flooding and lack of proper wastewater management hinder social and economic development and increasing water efficiency and improving water management are critical to balancing the competing and growing water demands from various sectors and users." In this report, the 2015 statistics were quite discouraging: 29% of the global population lacked safely managed drinking water supplies, and 61% were without safely managed sanitation services; 892 million people continued to practice open defecation; and only 27% of the population in least developed countries (LDCs) had basic handwashing facilities. On the positive side, the report indicated that preliminary estimates from household data of 79 mostly high- and high-middle-income countries (excluding much of Africa and Asia) suggest that 59% of all domestic wastewater is safely treated. In 22 countries, mostly in the Northern Africa and Western Asia region and in the Central and Southern Asia region, the water stress level was above 70%, indicating the strong probability of future water scarcity. In 2017–18, 157 countries reported average implementation of integrated water resources management of 48%.

6.4 Sustainability in the textile and garment industry

It is unfortunate that most international reports on sustainability consider the textile and garment industry as one of the leading industries with respect to sustainability violation. Few reports provided data evidence on the impact of the industry, but numerous reports and internet blogs were published only for the purpose of stirring human-right advocates and radical environmentalists against the industry. No one argues that manufacturing industries around the world have neglected the impacts on ecological footprint for many years and serious efforts must be made to minimize these impacts. However, as indicated earlier in this chapter, the world was made fully aware of sustainability issues only in the last quarter of the 20th century. Prior to this period, the world's focus was on enjoying the significant technological developments that have occurred since the Industrial Revolution that have certainly altered the world in many positive ways. One may also argue that engineers and technologists who have been heavily involved in numerous industrial developments in the 20th century should have realized ecological impacts of their designs and prevent them. This is a valid argument except for the fact that the focus of traditional engineering design has been primarily on the functional characteristics of products. Indeed, most of us engineers

who graduated before the beginning of this century had gone through the entire education programs without using the term sustainability explicitly or implicitly, and the term sustainability was only synonyms to features such as product durability and maintenance to prolong the service life of a product, which represent one dimension of sustainability as we know it today.

In industries like the textile or the petrochemical industry, dealing with sustainability issues requires new innovative concepts of product and process design. Imagine the world today without plastics, the most unsustainable material on earth. We use plastics of polyethylene and polypropylene to make millions of bottles and containers every day, we use melamine resin and polystyrene to make millions of plastic dishware, we use polyurethane to make foam cushions, we use polyethylene and polypropylene to make food wrap, we use PVC to make pipes and garden hoses, and we use polyurethane to make insulation foam. On top of all of that, the world produces more than 70 million tons of synthetic fibers every year made from plastics so that we can enjoy wearing warm, cool, and stylish clothing. Plastics take millions of years to decompose, and microplastic waste thrown in seas can end up in the seafood we eat. Can you imagine the world now without plastics? Perhaps, all consumers should switch to natural fibers such as cotton, the friendliest textile of all time; after all, the world can produce much more than the 100 million cotton bales (480 pound each), being produced today if demand increases. Unlike synthetic fibers, cotton fibers are biodegradable; they come from nature, and they go back to nature without environmental trace. However, even cotton has been considered as an unsustainable fiber by virtue of the excessive use of water, herbicides, pesticides, and synthetic fertilizers. In an article by Forbes Magazine in November 2017 (https://www.forbes.com/sites/quora/2017/11/02/are-cotton-t-shirts-sustainable-products/#7770bb663aba), it was stated

> *….between 1989 and 2014, the Aral Sea has nearly completely dried up… you can't call your crop sustainable when it's largely responsible for drying up an entire sea….. cotton production is water-intensive: it can take 2700 liters to produce a single T-shirt… cotton crops need to be treated with extraordinary quantities of pesticides and herbicides…. So: which fabrics are environmentally friendly? In short, none. Some industry sources say fashion is the world's second biggest polluter….*

6.4.1 The impact of the textile and garment industry on human well-being

In the context of sustainability, key parameters associated with human well-being include (a) employment, (b) wages, (c) gender equity, (d) education, and (e) health and safety. The contribution of the textile and garment industry to these parameters can be found in many national and international reports. However, data are scattered and often unadjusted with respect to demographic aspects or country gross domestic products (GDP). Given later are some of the key points related to human well-being parameters in the textile and garment industry.

Although statistics and data may vary from one source to another, most estimates indicate that in 2018, the global textile and garment industry was worth $4.5 trillion with global trade reaching $600 billion. The numbers of employees in the global garment and textile industries were estimated at a range from 55 million to 65 million people worldwide (https://data.worldbank.org/). This means that this great industry employs about 20% of the workforce worldwide, which is a very positive aspect that must be taken into consideration in the overall assessment of this industry. In the last 30 years, the industry has witnessed revolutionary technological development in terms of production speeds, condensation or shortening of processes, and automation. These developments have resulted in a significant reduction of labor intensity (about 30%). Nevertheless, the industry is still considered as a labor-intensive industry particularly in the garment sector, and it is likely to remain this way through most of the 21st century. In many developing and low-income countries, the average share of employment in the textile and garment industry to the total employment in manufacturing is 50%. In some countries such as Bangladesh, Vietnam, Lesotho, and Cambodia, this share may range from 60% to 90% [25].

With respect to wages, workers in the textile and garment industry in developing countries earn much lower wages than those in developed countries. This was one of the main reasons for the migration of the industry from Europe and the United States to Asia at the beginning of the 21st century. However, this aspect has nothing to do with human well-being since different countries are different in GDP, cost of living, currency rates, and the wealth of a nation. The World Bank developed an international comparison of GDP and per capita income by converting national income to a common currency based on purchasing power parities (PPPs) [24]. PPPs are obtained by expenditure categories (private consumption, investment, and government expenditure) and have become the standards for comparing different countries. In principle, a PPP is calculated using the formula $S = P_A/P_B$, where S is the exchange rate of currency A to currency B, P_A is the cost of product "x" in currency A, and P_B is the cost of product "x" in currency B. A fair comparison of wages between different countries should be based on this index to provide fair assessment of the relative impact of wages.

A better way to evaluate the effect of wage on human well-being is by evaluating the wage structure within the same country. According to a report by Overseas Development Institute (ODI) in 2008, it was found that textile wages were higher than garment assembly wages and the latter activities are more prevalent in poorer developing countries. This wage inequity has been steadily improving in many developing countries [25]. The ODI report also pointed out what workers would otherwise have earned had there been no textile and clothing industries and found that the industry offers women better employment opportunities than they would have had in the rural area and pays twice the rate of domestic servants in some countries like Bangladesh. Furthermore, while the textile and clothing industries were not among the best paid jobs, they were certainly not the worst even among manufacturing activities, let alone agriculture activities. In addition, the industry employs many women in the garment assembly firms from rural areas that are dominated by men and where gender inequalities are higher. According to the Sustainable Development Goals

Report 2018 by the United Nation [17], worldwide, the proportion of the world's workers living with their families on less than $1.90 per person a day declined significantly over the past two decades, falling from 26.9% in 2000 to 9.2% in 2017. This could not have occurred without a great contribution of the textile and garment industry. These are all positive aspects that should be considered in the overall assessment of the impact of the textile and garment industry on human well-being.

Regarding education, the industry still has a long way to go. It is important to realize that the industry relies on many unskilled and single-task labors. In some developing countries, many workers are illiterate or uneducated people who are working in the industry mainly to stay out of poverty. In one of the spinning mills we visited in South Asia, 80% of the workers were working primarily for food and basic living in a mill camp, and the working environment was largely unbearable, yet one can easily see a satisfaction mode among them. In an exchange, the author of this book had with the owner of this mill about the reason for this satisfying attitude, the answer was stunning: "it is because they do not know any better." Undoubtedly, this example represents one of numerous similar examples around the world in which providing education to workers is considered as a threat to companies because of fear that workers might seek better jobs elsewhere or perhaps become more informed about their basic rights.

The textile and garment industry needs to do a better job in educating workers not only for the worker's well-being sake but also more importantly for the sake of a better industry. It certainly makes no sense to have advanced technology surrounded or operated by uneducated employees. With more than 20% of the world workforce, the textile and garment industry can contribute immensely to the world's education. According to the Sustainable Development Goals Report 2018 by the United Nation [17], more than half of children and adolescents worldwide are not meeting minimum proficiency standards in reading and mathematics. This has led to the fourth goal of this report that calls for refocusing efforts to improve the quality of education since disparities in education along the lines of gender, urban-rural location, and other dimensions still run deep, and more investments in education infrastructure are required, particularly in least developed countries (LDCs).

Finally, the health and safety issue in the textile and garment industry has been one of the traditional challenges, not only because of the health hazardous environment that still exists in many companies but also because of the effects of the parameters indicated earlier, particularly poorness and education. In recent years, the spread of the social media and internet blogs, have resulted in numerous reports of human-right violations associated with safety and health in different industries including the textile and garment industry. However, most violation reports only reflect the effects not the root causes for the purpose of stirring human-right activities against the industry.

With respect to health, the high employment in the textile and garment industry inevitably places an automatic blame on the industry in health issues. This is particularly true in many developing countries. However, it should be noted that many of these countries suffer numerous health issues outside the textile and garment

industry. International reports are staggering in this aspect. According to the Sustainable Development Goals Report 2018 by the United Nation [17], in 2015, 29% of the global population lacked safely managed drinking water supplies, and 61% were without safely managed sanitation services. In 2015, 892 million people continued to practice open defecation. In 2015, only 27% of the population in LDCs had basic handwashing facilities. As will be discussed shortly, the industry has been a major consumer of good water and a major polluter of water worldwide.

The concern about human health also stems from within the textile industry as a result of some of the current approaches of processing that are environmentally and physically toxic. A study titled "Measuring Fashion, Environmental Impact of the Global Apparel and Footwear Industries 2018" by Quantis [26] indicated that damage to human health due to pollution is caused by the release of substances that affect human beings through acute toxicity, cancer-based toxicity, respiratory effects, increases in UV radiation, and other processes. Using a methodology in which substances are weighted based on their ability to cause a variety of damages to human health, these impacts were measured in units of disability-adjusted life years (DALY), which combine estimations of morbidity and mortality from many causes and determine the overall disease burden, expressed as the number of years lost due to ill-health, disability, or early death. According to this study, the process of dyeing and finishing contributed by 33% to the total DAL, yarn preparation was second by 27%, fiber production was third by 21%, and fabric production was fourth by 11%.

The discussion earlier clearly indicates that human well-being has been at the center of concern of the textile and garment industry with significant improvements in some related parameters and need for improvement in others. There is nothing easier than criticizing an industry for not doing enough in terms of improving human well-being as effects are easier to observe. The problem, however, stems from diagnosing the causes and working on reliable and cost-effective remedies. The textile and garment industry is under continuous pressure to produce masses of products at the lowest cost possible including labor cost and benefits. It has met this challenge for hundreds of years despite the few cents per pound profit it makes in virtually all traditional products. Today, the industry's share in the profit margin of end product is still among the lowest of all industries. This is an industry that uses commodity raw materials in masses and produce products in masses. Consumers need to realize that the profit that the textile and garment industry makes is not measured with respect to the profit a retailer or a designer make when selling a pair of jeans or a designer T-shirt. The industry's profit is determined on "per-pound" basis. It is an industry that can take a single bale of cotton fiber and produce 215 pairs of jeans, 250 bed sheets, or 400 sport shirts per bale. Yet, it will only earn less than 15% of total profit margin of any of these products, with the lion share (more than 75%) going to retailers and brands. The industry has lived with this profit inequity for so many years to the point of full satisfaction for the lack of other options. Retailers or brands cannot be entirely responsible for this profit inequity, and the textile and garment industry must shift to more product-focused and value-added designs to gain a bigger share of the profit margin.

6.4.2 The impact of the textile and garment industry on ecological footprint indicators

The textile industry can be divided into two main categories of processes (Fig. 6.1): (a) basic material production processes and (b) end-product manufacturing processes. Basic material processes consist of fiber production, yarn manufacturing, and fabric manufacturing. Machines used in this category are designed to produce masses of production units (fibers, yarns, or fabrics) that are typically sold by mass (pound or kilogram). End-product processes consist of machines or operations designed to meet customized requirements for different products. One of the main obstacles facing sustainable developments in the textile and garment industry is the lack of integration between different processes. Different materials are typically produced in different facilities by different companies and often in different countries. This creates a great deal of difficulty in establishing integrated sustainable processes over the entire life cycle of a product.

In the textile and garment industry, the motivation to implement sustainable development may vary significantly from one culture to another and from one organization to another. Companies that are serving domestic markets in countries that are lacking consumer's awareness and effective enforcement means of environmental and human-right regulations will likely be demotivated to implement sustainable development as a result of the lack of short-term benefits and the lack of government support. On the other hand, large companies that are operating globally, exporting their products to different regions in the world, must immediately begin to establish sustainable development strategies as this will be the only way for them to survive in the global market. It is the author's opinion that sustainability will ultimately result in another shake up of the textile and garment industry like the one that occurred at the end of the 20th century, which was due to differential labor cost. The pressure of the new shake up will certainly be higher on Asia and many of the developing countries.

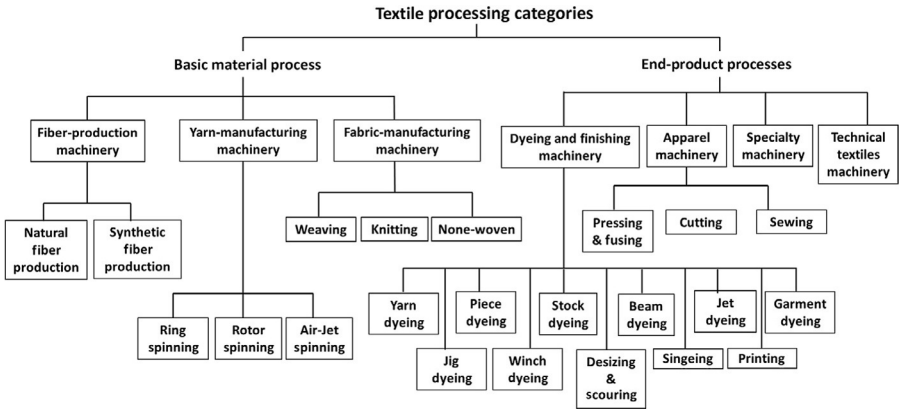


Fig. 6.1 Categories of textile processing.

On the other hand, industrial countries will have huge responsibilities as they have been a major contributor to waste, pollution, and environmental distractions over the last 50 years.

The challenge of meeting integrated sustainability development is much bigger than an industry or an organization can meet. It takes governmental goals and policies, realistic economical approaches, major funding for new sustainable innovations, and substantial alteration of today's global culture of high consumption and obsolescence before depreciation. It also takes significant innovation in renewable energy, recyclable materials, and fair distribution of planet resources to meet these challenges. Fortunately, the world is moving in the right direction in many sustainability aspects [17]. This progress was made primarily as a result of awareness of environmental impacts by most governments around the world. The journey is obviously still very long, and holistic designs aiming at achieving sustainable developments must be implemented in the next few years.

Most reports about the impact of the textile and garment industry on ecological footprint indicators are unfavorable. The Natural Resources Defense Council (NRDC), which is a United States-based, nonprofit international environmental advocacy group, indicated that the global textile and garment industry was responsible for about 1.72 billion tons of carbon dioxide in 2015, more than 5.4% of the 32.1 billion tons of global emissions in the same year. The same organization also reported that the textile industry is the world's second most polluting industry after the oil industry. In 2018, the UN Climate Change News (https://news.un.org/en/news/topic/climate-change) indicated that the fashion industry, including the production of all clothes, contributed to around 10% of global greenhouse gas emissions due to its long supply chains and energy intensive production. The United Nations Framework Convention on Climate Change (UNFCCC, https://unfccc.int/news/un-helps-fashion-industry-shift-to-low-carbon) indicated that fashion sector's emissions are likely to rise by more than 60% before 2030, if transformation toward a sustainable fashion industry fails to materialize soon.

Regarding water footprint, the United Nations Framework Convention on Climate Change (UNFCCC, https://unfccc.int/) indicated that cumulatively, the textile and fashion industry produces about 20% of global waste water. Furthermore, 85% of textiles end up in landfills or are incinerated when most of these materials could be reused. Textile mills are also blamed for being a 20% contributor to the world's industrial water pollution, using thousands of toxic chemicals during production, some of which are found to be carcinogenic. In China, official data from the Ministry of Environmental Protection reveal that the textile industry was the third largest source of industrial wastewater in the country. In 2015, the industry produced 1.84 billion tons of wastewater effluent, accounting for 10.1% of China's total industrial wastewater discharge.

The data earlier certainly call for a continuing effort toward more sustainable textile and garment industry around the world. As will be discussed in the next section, the most critical aspects of design for sustainability are a detailed life-cycle analysis based on reliable database of all indicators of ecological footprint.

6.5 Engineering design for sustainability

Engineering design should be based on developing a problem model leading to a solution model. The problem model is derived from exploring the different factors influencing a certain product performance, and the solution model is derived from the relationship between these factors and the desired functional performance characteristic of a product. This was the essence of the "concept-modeling-optimization-manufacturability" system, CMOM, presented in Chapter 5. Problem models are normally initiated by scientists who perform scientific analysis using inductive reasoning to build a relational model. In the context of sustainability, the fundamental problem is to develop products and processes that "*meet the needs of present without compromising the ability of future generation to meet their own needs*." This is not a typical problem that engineers normally expect to face because it does not point out an explicit target or objective that engineers can fully understand and perform design analysis to meet. For this reason, engineers must gain a good knowledge base of the concept of life-cycle engineering and technology-based solutions to the sustainability problem. This knowledge base may stem from scientific studies on sustainability of related fields, life-cycle analysis, or exploratory studies on sustainability problems related to the product or process under consideration.

In the absence of a specific problem model related to the product or process under consideration, engineers must begin with a basic conceptual model before they can develop their own problem models. In all situations, the best general problem model of sustainability is the IPAT equation, $I = P \times A \times T$, in which I is the environmental impact, P is the number of people, A is the number of products per person, and T is technology. The IPAT equation suggests that to minimize the environmental impact, population growth must remain under controlled rate, which is a social aspect; consumption must be rationalized, which is an economical aspect, and supportive sustainable products and processes must be developed, which is primarily a technology aspect. Technology is driven by science and engineering design as explained by the "Engineering Operating System, EOS" discussed in Chapter 4, in which engineering design is the vehicle that transform science to technology for the sake of producing products of optimum performance. Therefore, sustainable development requires placing the entire OES in the interface between environment, economy, and society as shown in Fig. 6.2. In the following sections, we elaborate on these three factors.

6.5.1 *Society: The* P*-factor in the IPAT equation*

As indicated earlier, one of the driving forces leading to the increasing concern about sustainability has been the exponential growth in the world population since the beginning of the 20th century. The one billion mark of world population was not passed until the early 1800s; the two billion mark was not until the 1920s. In the following 80 years and in the year 2000, the world reached over 6 billion people. Human population is perhaps the only natural resource that continues to grow and increase. However, its survival required other natural resources including water, air, coal, oil,

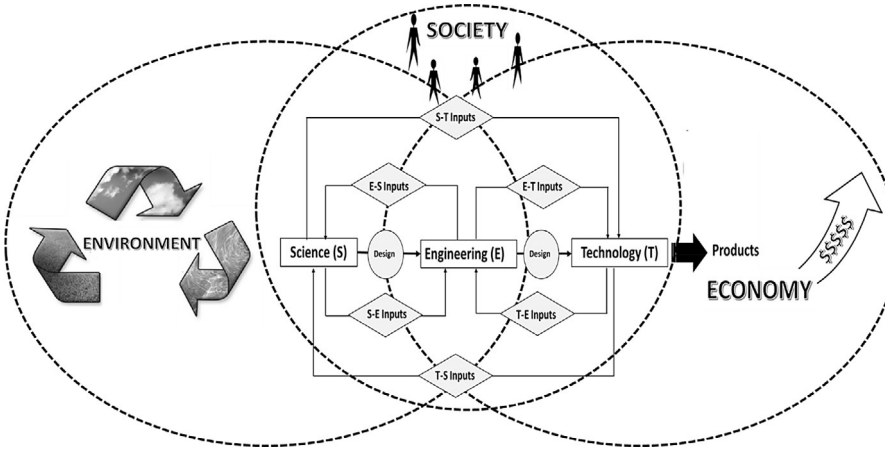


Fig. 6.2 The Engineering operating system (EOS) in the interface between environment, economy, and society.

natural gas, phosphorus, other minerals, iron, soil, forests, and timber. These natural resources are now being consumed or depleted at much higher rates than population growth as evident by the data of ecological footprint of production and consumption and biocapacity statistics mentioned earlier. In addition, natural resources are not evenly distributed around the planet. Countries such as Japan, South Korea, Italy, and Singapore have very limited natural resources except for human assets that have been utilized effectively and efficiently to place these countries on top of the industrial world. Other countries have abundant amounts of natural resources. For example, China, the second largest economy in the world, is also considered as the largest owner of natural resources including coal, rare earth metals, timber, phosphates, cobalt, copper, manganese, and silver. Saudi Arabia has 20% of the world's oil reserves and huge amount of natural gas. Russia has the biggest mining industry in the world producing mineral fuels, industrial minerals, and metals. The United States has been one of the leading producers of coal for decades, and it accounts for over 30% of global coal reserves. Other US resources include substantial copper, gold, oil, and natural gas deposits.

Environmentalists consider population growth as a potential threat to environment by virtue of people consuming more and wasting more. Some governments also consider excessive population growth as a hindering factor against economic growth. Those are typically the governments that have problems in utilizing human assets to increase their gross domestic product (GDP) leaving them with serious concerns about providing food, health, and education services to an unproductive society. Other countries such as Japan and Korea welcome population growth as a result of the increase in their senior citizen population and the need for younger generation. These countries also know how to utilize human assets and control population consumption and waste.

In view of the earlier points, population growth represents a societal moving-target factor, which is difficult to predict particularly from one country to another. On one hand, population growth can be attributed to inadequate birth control in many cultures. On the other hand, the technology aspect represented by significantly improved human living environment and health care has been one of the driving forces for population growth. According to Goal 3 of the UN Sustainable Development Goals Report-2018 [17], mortality rate has been in a continuous decrease, and in the 2000–16 period, the under-5 mortality rate dropped by 47%, and the neonatal mortality rate fell by 39%. Over the same period, the total number of under-5 deaths dropped from 9.9 million to 5.6 million. This means that population growth is largely a work of technological development in health care, food and nutrition, and better infrastructures. Therefore, the fundamental question is as follows: can the growing population today enjoy a better living environment without causing deterioration in tomorrow's population living environment?

6.5.2 Economy: The A-factor in the IPAT equation

From a sustainability perspective, one may argue that the issue is not necessarily the number of people on the planet, but rather the consumption rate of natural resources by people. As Mahatma Gandhi once said, "the world has enough for everyone's need, but not enough for everyone's greed." This visionary quote is now evident by the fact that due to variation in consumption, many highly affluent nations leave a much greater footprint on our planet than low affluent nations. Some low-income regions around the world emit less than 1 ton of CO_2 equivalent per person per year, while some high-income regions around the world emit 6–30 tons of CO_2 equivalent per person per year.

Since the beginning of the 21st century, every year passed, the world population has increased by nearly 80 million people. This is roughly a linear increase at an average rate of growth of about 1.24%. Meanwhile, the consumption has increased by a rate of about $2.45 trillion every year. This is an average rate of consumption of about 5%, even though the world's consumption was decreased by as much as 5% in some years. This provides a clear evidence that the growth of population will yield a corresponding growth in consumption. Thus, P and A are highly correlated. Another key economic factor is the increase in urban population, which represents the largest consumers and disposers of goods. This has increased from 46% in 2000 to 54% in 2017. Over the same period, the number of people per square kilometer of land has jumped from 40 to 50. This means that countries that have been consuming less goods and causing less ecological footprint are now contributing to the sustainability problem by consuming more and wasting more. Indeed, the two largest-population countries in the world, China and India (nearly 37% of the world population), are becoming more urbanized and industrialized, which means that they will consume more goods, energy, and other resources.

From an economic viewpoint, business organizations in virtually all cultures have been the greatest beneficiary of population growth and human's consumption of goods. In response to exponential population growth, productions of necessities such

as food, clothing electricity, fuel, and housing have increased immensely. On the other hand, the increase in the world urban population accompanied by advanced technology has introduced new creative business approaches primarily focusing on creating "wants" or luxurious products that are characterized by short-use life cycle as a result of rapid obsolescence rate. To make matters additionally complex, yesterday's "wants" have become today's needs as one cannot imagine the world today without new models of smart phones introduced every year or fast-changing fashion every season. These developments have altered the traditional concepts of supply and demand to the point that demand is no longer based primarily not only on price but also and, often more overwhelmingly, on the ability of business organizations to introduce newer and more attractive products.

To further illustrate the earlier point, it will be useful to consider the classic concept of demand elasticity. As can be seen in Fig. 6.3, the price-quantity relationship in a linear demand profile is associated with a unique elasticity of demand, E, defined as the degree to which demand for a good or service, Q, varies with its price, p, or

$$E = \frac{percent\ change\ in\ quantity}{percent\ change\ in\ price} = \frac{\triangle Q\%}{\triangle p\%}$$

An elastic demand means that a slight decrease in price will yield a very large increase in sold quantities, and an inelastic demand means a large decrease in price will only yield a small increase in sold quantities. Some economists like to categorize the

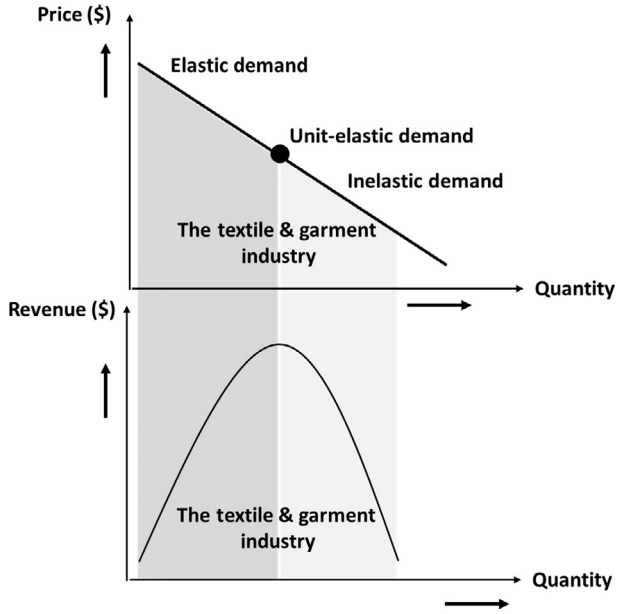


Fig. 6.3 Demand elasticity of the textile and garment industry.

clothing industry as being highly inelastic. This view treats basic clothing as an essential item like food or medicine, which typically do not sell significantly more or less with change in price. This may be true if textiles and clothing are only used for basic needs, which is no longer true by virtue of the fast fashion trends over the last 20 years. As a result, a textile and garment company today can be anywhere on the supply-demand curve. Some companies operate in the elastic zone of demand by reducing their prices to sell larger quantities and, thus, increasing their revenues. In this case, the main concern of these companies is to reduce manufacturing cost to justify price reduction. Most yarn and fabric producers follow this basic strategy. Other companies rely on producing value-added technical textiles and attractive fashion products that allow them to operate in the inelastic zone yet creating revenues and profits. Indeed, going from one company to another, one can see that different companies can be in different zones on the price-quantity demand curve as a result of the complex global supply chain of the industry and due to the fact that this industry has suffered all kinds of market turbulences including market over saturation of goods; the availability of numerous substitutes; changing brand loyalty; and variation in consumer's wants and needs by income, region, and culture.

A sustainable process model should be based on producing value-added products not only in terms of functionality and styles but also equally important in terms of human well-being and environmental factors. A textile and garment company meeting the $P \times A$ criterion of the IPAT equation must develop creative approaches in which more products will inevitably be produced to meet the population's growth, yet at a minimum waste of natural resources. In the face of high consumption (e.g., fast fashion, disposable products, tires, and carpets), systematic approaches to reutilize used products should represent a critical element in the industry's practice. This will create more manpower than machine power and generate more revenues and higher profits for the company.

6.5.3 Technology: The T-factor in the IPAT equation

It follows from the earlier discussion that achieving sustainable development in the textile and garment industry must be based on revolutionized concepts of the third parameter of the IPAT equation, which is technology. Unfortunately, technology in the IPAT equation is considered as an independent factor of direct effect on environmental impact, with more technology resulting in higher impact. For this reason, Ray C. Anderson (1934–2011), the founder and chairman of Interface Inc., recommended that technology should be in the denominator of the IPAT equation, $I = P \times A/T$, meaning it should be treated as a positive index, the higher value of which, the lower the ecological impact. As it is well known, Interface Inc., a company that started in 1973, was challenged 20 years later (1994) by its founder Ray Anderson to develop creative technology that can offset the I-index in the IPAT equation in what was described as "mission zero," or the elimination of negative impact on the environment by the year 2020. The giant commercial tile company formed the so-called Eco Dream Team to meet its goals. The principle of this mission was based on many aspects including elimination of waste; elimination of toxic substances from products,

vehicles, and facilities; using renewable energy; and closing the loop by redesigning processes and products to close the technical loop using recovered and bio-based materials. In the 2000–19 period, Interface Inc. has managed to increase its stock value by 200%, and in some years, it reached 400% gain in stock value suffering only during the 2008 recession of this period.

It is critical that both product and process designers understand that for humans to survive on earth, today's linear economics of scale that is based on producing more, selling more, and wasting more must cease. Products that are produced for limited use and then irresponsibly discarded will end up in landfills or in the ocean. This type of economy will not be compatible with today's biocapacity, and it will eventually lead to more restricted styles of living that will likely displease future generations. According to Walter Stahel, the pioneer of the concept of circular economy, the future will dictate that we must follow innovative approaches in which we will need more from less (economies of scope). In today's textile and garment industry, the common approach is to continue to manufacture products that must be sold to maintain GDP growth, which means maximizing throughput. In a circular economy, growth means an increase in quantity and quality of material stocks, which can be reused infinitely. The emphasis of a circular economy is on renewable and infinite resources and shifts away from nonrenewables. For this reason, it has been heavily promoted by the United Nation and by several governments and businesses around the world. In the context of science, circular economy is still superficial and unorganized. It seems to be a collection of vague and separate ideas from several fields and semiscientific concepts [27].

Innovations in sustainable technology will certainly yield more economic benefits and meanwhile serve the best interest of human being. The key emphasis in these innovations should be on maximizing eco-efficiency defined by [28–31]

$$Eco-Efficiency=\frac{the\ value\ of\ a\ product\ or\ service}{lifecycle\ \ impact}$$

The earlier expression aims at integrating environmental considerations into product design with the primary design theme being product life-cycle analysis. The main goal of these strategies is to minimize the consumption of natural resources and energy and the consequent impact on the environment while maximizing the benefits for customers [30,31]. Many driving forces and barriers for an organization to implement sustainable design have been listed in the literatures. Driving forces for sustainable development include [31–33] (a) the opportunities for innovation, (b) the expected increase of product quality, and (c) the potential market opportunities. These factors reflect consumer demands, governmental rules and regulations (or legislations), and industrial sector initiatives. Eventually, all organizations will be required to adhere to some sort of sustainable developments to be able to fit in the global organizational structure and to avoid economic sanctions. The future organization will exist not only based on the product or the service it provides but also and perhaps more importantly based on its commitment to humans and the environment. Barriers against sustainable developments include [31–33] (a) the struggle of where to begin and how to initiate

sustainable strategy; (b) short-term versus long-term benefits; (c) finding innovative nontraditional approaches of sustainable development; (d) who is responsible for sustainable development, the organization or the government; (e) consumer's lack of awareness of the importance of sustainability; and (f) consumer's willingness to pay more for sustainably responsible products at least on short-term basis and until the economics of scales prevail.

6.6 Engineering design for sustainability in the textile and garment industry: Sustainable process model

In the textile and garment industry, the development of a sustainable process faces many challenges that are results of long unsustainable practices. These include [34] (a) high energy utilization, (b) inadequate manpower-to-machine power ratio, and (c) poor waste management. These challenges are briefly discussed in the following sections.

6.6.1 Energy utilization

The textile industry is among many other industries that need more innovations in terms of developing processes that are energy efficient. Some studies [35–37] estimated the extracted energy consumption to manufacture 1 ton of cotton garments at 66,648 kWh and that to manufacture 1 ton of polyester garments at 91,508 kWh. In recent years, many concerns have been raised about the use of traditional fossil fuels and the need to use alternative fuel sources. These concerns are related to the loss of energy efficiency, and the rate of emission caused by fossil fuel energy production. Unfortunately, the world is going slowly in the development of alternative energy because of the amount of investment needed to make them viable. In developing a sustainable process model, options of energy use should be entertained for short-term and long-term development of sustainable process [38,39]. For example, the use of coal as a source of energy should be minimized or eliminated. It should be known that as much as 70% of the energy produced from burning coal can be lost in the power plant due to poorly designed and inadequately insulated furnaces, from the amount of electricity that emerges from the power plant up to 10% can be lost due to inefficiency in the transmission lines, and from the amount of electricity transmitted to manufacturing lines up to 10% can be lost due to inefficiencies in the motors used. By using alternative energy sources, all these losses can be avoided.

In general, the use of fossil energy sources should be minimized or avoided. These include oil, coal, and natural gas, which are nonrenewable resources that are formed when prehistoric plants and animals died and were gradually buried by layers of rock. Instead, the process model should account for the use of renewable energy generated from natural processes that are continuously replenished. This includes sunlight, geothermal heat, wind, tides, water, and various forms of biomass.

An energy-efficient process model should be based on evaluating current machines in terms of motor efficiency, power transmission efficiency, and worn parts that can

result in higher energy consumption. In other words, machine evaluation and maintenance must be integrated into the design of a sustainable process model. It is also important to account for load energy, which is the energy required to process different types of material. Different fibers will typically exhibit different processing propensities due to dimensional and surface characteristics, elastic resilience, and the presence of nonfibrous particles. As a result, a sustainable process model should be developed in view of the type of raw material used in manufacturing the product. This can be a complex aspect as it may require an optimization of a combination of factors including machine speed and chemicals used. Unfortunately, databases on this aspect are missing, and scientific studies are needed to establish comparative data on load energy for different raw materials.

Another important aspect of energy utilization is the number of machines required to manufacture a certain product. In a sustainable environment, smaller number of machines could result in substantial economic benefits and lower energy consumption. Every machine unit used in a manufacturing line will inevitably have an ecological footprint. This means that a reduction in the number of units required to manufacture a product will certainly have a positive ecological impact. Designers of textile machinery have done a great job in shortening the number of processes required to produce intermediate textile products and in automating many manufacturing operations including machine self-adjusting using autoleveling systems, online process control, and automatic transportation of material from one stage of processing to another.

In the last 50 years, new technologies have been introduced for the sake of shortening processing lines and reducing manufacturing cost. For example, the use of open-end spinning instead of ring spinning in the production of carded coarse yarns has resulted in eliminating processes such as roving and winding. Fabrics that can be knitted instead of woven result in substantial reduction in many yarn-to-fabric manufacturing stages. Another new innovation, which is worth mentioning is the 3-in-1 machine introduced in 2018 by Mayer & Cie, one of the giant knitting machine companies. The 3-in-1 concept is based on combining spinning, winding, and knitting machines into one machine. In this machine, knitwear is manufactured not from yarn but straight from the fiber roving. The process starts with fiber roving from the spinning mill used directly to knit fabric, thus avoiding the spinning process and eliminating the need to produce a spun yarn. The fiber strand, or the roving, is fed to a drafting system to provide the necessary strand thickness or count. Prior to the knitting process, the roving is automatically cleared of irregularities such as thick or thin places. These irregularities are identified by the roving sensor in a 100% online process and reported to the machine control. In an automated process, irregularities are eliminated, and flawless knitting is then resumed. This 3-in-1 concept is claimed to use one-third less energy, take up much less space, and generates less waste and less CO_2.

Ideally, a sustainable process model should aim at lower energy consumption and effective use of manpower. The trade-off between labor reduction (manpower) and energy consumption resulting from the use of these technologies deserves a comprehensive study by engineers and technologists in the industry. Future developments toward energy-efficient processes should focus on the nonwoven industry in which

fibers are converted directly into different fabric structures without the need for producing fiber strands. Currently, the focus of the nonwoven industry has been on industrial and technical applications. The use of nonwovens in the garment industry has been limited due to the relatively higher stiffness of nonwoven fabric compared with knit or woven fabrics making it less pliable and less conforming to human body movement. Innovations in this field to produce more flexible and more durable structures will certainly result in a significant leap in the sustainable development of the textile and garment industry. The fact that nonwovens are made straight from fibers will also allow much easier recycling processes of nonwoven products, particularly when nonwovens are mechanically or air bonded.

6.6.2 Manpower-to-machine power ratio

The ratio of manpower to machine power has been considered as one of the most debatable issues of sustainable development. Most industries have dealt with this issue primarily from an economical viewpoint. Machine power requires significant capital investment for purchasing machines; it is also associated with higher energy consumption and continuous maintenance cost. However, costs associated with using machine power are highly predictable, and estimates on the return on investment can easily be calculated over a long period of time. Furthermore, the use of machine power is associated with high consistency in the quality of products particularly when computers and automation are used in controlling machine operations and transporting materials from one stage of processing to another. However, replacing labor by machines has not been historically welcome in many overpopulated countries in which millions of unskilled labors have relied on the textile industry as the primary source of making living.

As indicated earlier, the replacement of manpower by machines have been coupled by an increasing trend toward automation. In today's textile technology, one can find different companies implementing different levels of automation including: fully automated processing lines, semiautomated processing lines, and largely manual processing lines. The choice of the level of automation typically depends on many factors including the size and the volume of business of a company, the supply and demand rules, the complexity of the manufacturing operation, the production rates required, and the cost of manufacturing. From a sustainability perspective, automation should be considered as a positive trend to assist easing labor work and not to totally replace manpower. In addition, manpower working in an automated or semiautomated process should exhibit high levels of qualification to maximize the use of technology. In other words, a fully automatic machine does not optimize or maintain itself; it requires qualification and experts and a great deal of independent process analysis that can yield optimum settings and logistical means of maintenance scheduling and rotation. These are all human aspects that cannot be overlooked in adopting automated technology.

Traditional practices in the textile industry have been based on determining the number of workers needed for a manufacturing operation using trial and error. Managers make their best estimate of labor requirements for a given number of machines

and then use trial runs to fine-tune the estimate. This practice needs to be transformed into an integral element of a sustainable process design to accommodate manpower. In the design analysis of a sustainable process model, it will be important to utilize the concept of "overall equipment effectiveness (OEE)." This is the ratio of actual production time to planned production time. This concept has been implemented in many industries, and only recently, it has been used by the author and other experts in some projects in the textile industry. The OEE is basically determined by a single index derived from a performance metric of three key process-related parameters. These parameters are availability, performance, and quality. Availability is an indirect measure of machine efficiency determined by the following equation [40,41]:

$$Availability = \frac{Actual\ Operation\ Time}{Planned\ Operation\ Time}$$

The actual operation time is the time during which the machine is in full production. The planned operation time is normally determined based on a time frame not only encompassing the actual operation time but also accounting for anticipated machine idling and operator's involvement in serving the machine during production, which may result in temporary delay of production. This analysis will obviously vary with the variation in machine type, the production plan, and the level of automation.

In semiautomated processes, a sustainable process model should be based on a full understanding of human involvement in the process. Humans can indeed play a major role in mill organization, production logistics, handling quality issues, and meeting production targets. In general, manpower should be divided into two main categories: basic operators and supporting manpower. These two categories of manpower must work together in a coordinated fashion to avoid excess unnecessary labor in some operations. Furthermore, a sustainable process model should account for the fact that labor performance is not constant but rather dynamically variable; overworking labor could yield many negative results, and when the performance of a worker drops, the production output also drops no matter how automated the technology is. Improper monitoring of worker's performance will result in low production standards and increase machine maintenance.

A sustainable process model should also account for working versus idle time duration. For example, a planned working shift (8 h or 12 h) should be divided into two periods: operation period and downtime period. Operation period represents the proposed time for continuous production, which can be divided into normal expected operation period, and unplanned downtime. Downtime period is based on management decision to stop the production process due to resetting machines, making preventive maintenances, or rearranging production logistics. These are all factors that determine machine efficiency and manpower time for both fully automated and semiautomated processing lines. This leads to the second parameter, which is performance. It accounts for speed loss, which includes any factors that cause the process to operate at less than the maximum possible speed or rated speed when running. This includes machine wear, substandard materials, misfeeds, and operator inefficiency. The remaining available time is called actual operation time. Accordingly,

performance is defined as the ratio of actual operation time to planned operating time and accounts for speed loss. Machine ideal cycle time is the minimum cycle time that the process can be expected to achieve under optimal conditions for a given part. Therefore, when it is multiplied by total product units, the result is actual operation time. Machine ideal cycle time is sometimes called design cycle time or nameplate capacity. Since rate is the reciprocal of cycle time, performance is calculated as

$$Performance = \frac{(Machine\ Ideal\ Cycle\ Time \times Total\ production\ Units\ Produced)}{Planned\ Operation\ Time}$$

In the textile industry, the trend has been to stretch machine production for as long as it can possibly take for the sole sake of meeting production target. As a result, machine maintenance has been largely overlooked. For example, the duration period between card wires change in a carding machine is commonly three to four times the recommended duration by machine designers. This could automatically result in progressively poorer quality, higher energy consumption, and rapid wearing out of machine parts, all of which can eventually result in higher production cost and inefficient process.

The quality parameter considers quality loss due to produced units that do not meet quality standards including pieces that require rework. Quality is the ratio of actual productive time (time for good pieces produced) to planned operation time (time for total pieces), and it is calculated by

$$Quality = \frac{Good\ Product\ Units\ Produced}{Total\ Number\ of\ Product\ Units}$$

As indicated earlier, the overall equipment effectiveness (OEE) score combines availability, performance, and quality into a single number that can provide a complete measure of machine efficiency. It is defined by the ratio of actual production time to planned production time:

$$OEE = Availability \times Performance \times Quality$$

Design analyses stemming from the OEE concept have been implemented in modern cotton ginning for many years. The primary function of ginning is to separate cotton fibers from the seeds while maintaining seed integrity and producing fibers of high quality. Fig. 6.4 illustrates the flow of cotton through the different stages of the ginning process [42,43,44]. Seed cotton coming from the field is typically wet and muddled with trash particles, leaf, dirt, rocks, and other contaminants. As a result, seed cotton must be precleaned and then dried using hot air to remove excess moisture before the ginning process. The temperature of the conveying air is regulated to control the moisture content upon drying. Dried seed cotton is then fed through a number of cleaners that essentially use revolving spiked cylinders rotating at high speeds (400–500 rpm). These cylinders scrub the cotton over a series of grid rods or screens; agitate the cotton; and allow fine foreign materials, such as leaves, trash, and dirt, to pass through the openings

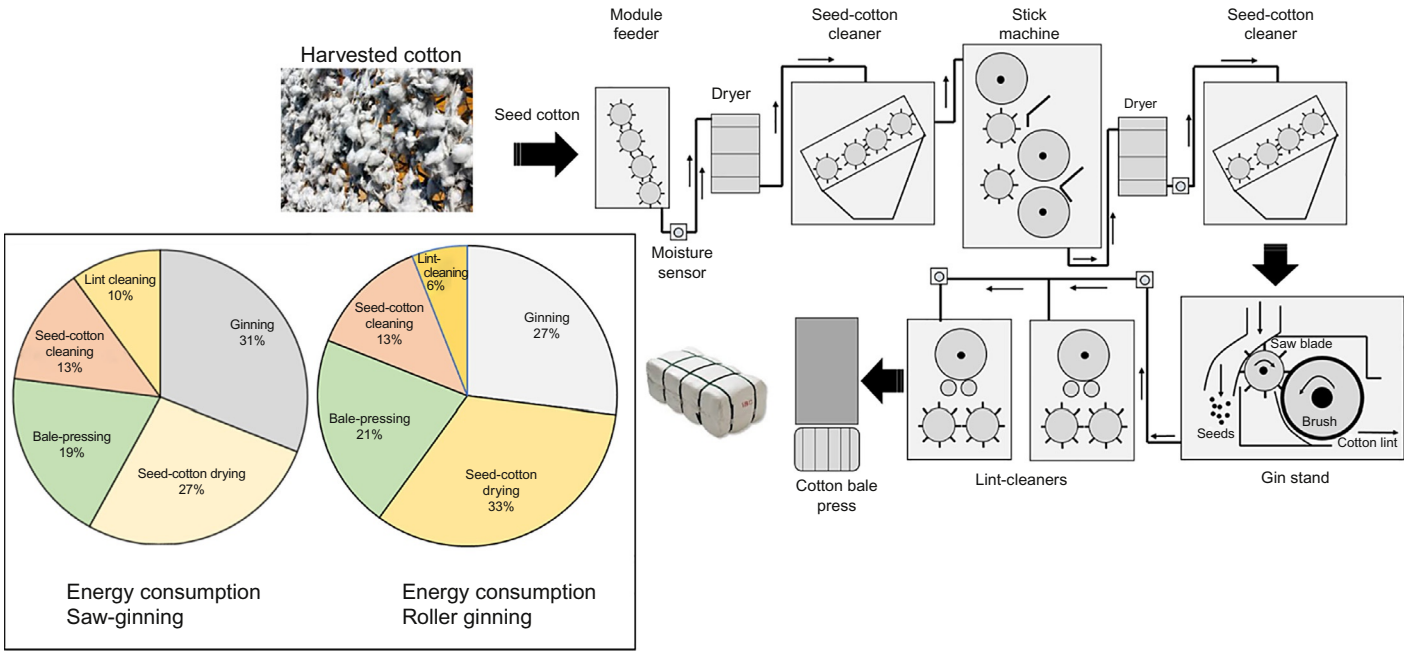


Fig. 6.4 Flow of seed cotton through the ginning process energy distribution derived from Refs [42–44].

for disposal. The so-called stick machine is designed to remove stick, stems, burrs, and various larger foreign objects. This process is then followed by another drying unit before seed cotton is finally fed to the ginning machine.

Two types of gins are commonly used globally: the saw gin and the roller gin. In saw ginning, cotton enters the saw gin stand through a huller front; the saws grasp the cotton and draw it through widely spaced ribs known as huller ribs; the locks of cotton are drawn from the huller ribs into the bottom of the roll box. The ginning action is caused by a set of saws rotating between ginning ribs. Roller-type gins are typically used for separating extra-long staple cotton lint from seed. A typical roll-gin machine consists of a leather ginning roller, a stationary knife held tightly against the roller, and a reciprocating knife that pulled the seed from the lint as the lint is held by the roller and stationary knife. Upon ginning, cotton is conveyed from the gin stand through lint ducts to condensers, formed again into a batt, which is removed from the condenser drum and fed into the saw-type lint cleaner. The saw carries cotton under grid bars, which are aided by centrifugal force and remove seeds and foreign matter. Finally, cotton fibers are pressed into bales to be shipped to the spinning mill. Typically, a cotton bale will weigh 500 lb. and measures 54 in. × 27 in. × 48 in. Fibers in the bale are typically compressed to a density ranging from 10 to 15 lb./ft^3. Some bales are compressed to a density of 25 lb./ft^3 and to measures of 56 in. × 28 in. × 24 in. for shipping to a distant area. Cotton bales are also wrapped in burlap, cotton, polyethylene, or polypropylene bagging. The bale wrap is commonly secured using a series of metal straps to enforce the compressed state of the fibers.

Past ginning practices were associated with many concerns including air pollution and labor exposure to environmental health hazardous conditions including breathing dust and safety issues. In the 1960s, about 3 man-labor per bale was needed in the ginning process. New ginning process models now resulted in a reduction of labor to about 0.55 man-labor per bale [42,43]. This was a step in the right direction since less manpower in this process meant avoiding human-related adverse effects. With respect to energy consumption, saw ginning typically operates at much higher production rates (about 44 bales/h) than roller ginning (about 25 bales/h). Yet, roller ginning will consume higher energy (about 56 kwh/bale) than saw ginning (35 kwh/bale). One of the reasons for the higher energy consumption in roller ginning is the higher energy required for drying and pressing cotton in roller ginning. Most roller-ginned cotton is manually harvested, and the cotton can be left in the field for many days before moving to the gin stand absorbing more moisture. Roller-ginned cotton also requires less lint cleaning after ginning. Overall, by comparison with the 1960s, electrical energy consumption in ginning has decreased by 19% to 34%.

6.6.3 Waste management

As indicated earlier, the biggest source of waste in the textile and garment industry is fibers. Fiber production has increased significantly since the beginning of this century, and the more fibers produced, the more fiber waste will be expected. The 2017 market statistics indicated that worldwide, fiber production is at a record high of 100 million

metric tons [45]. This is a substantial increase by comparison with 1950 in which global fiber production was less than 10 million metric tons. Since the early 2000s, polyester fiber has dominated the fiber market. In 2017, the market share of synthetic fibers reached 60%, with polyester fiber alone at 51% of the total global fiber production (more than 53 million metric tons); nylon fiber was about 5.5%, and other synthetic fibers were about 5.5%. Cotton fiber was second in total market share reaching 25% (about 26 million metric tons); wool fiber was about 1 million metric tons in 2017, or 1% market share, long-vegetable fibers including jute, linen, and hemp were at about 5%, and silk and down had market shares of less than 1%. Cellulose-based man-made fibers that are typically considered as a separate category by virtue of the wet processing involved in making these fibers had a market share of 7% (roughly, 6.5 million metric tons).

As illustrated in Fig. 6.1, fibers are converted into a wide range of textile products using many types of processing. Ideally, a life-cycle process model dealing with fiber waste must begin with the manufacturing process that converts fibers into textile products and continue all the way until the end of service life of textile products. Unfortunately, a comprehensive database covering fiber waste of all fiber types is yet to exist. Such database will be critical in realizing the total magnitude of fiber waste and how different fibers are associated with different types and amounts of waste. Therefore, only few examples of fiber waste will be presented here for the sake of demonstrating the magnitude of fiber waste during manufacturing.

Textile waste can be divided into two major categories [46]: (a) preconsumer waste and (b) postconsumer waste. Preconsumer waste is encountered during processing of fibers into yarns, fabrics, and garments. Postconsumer waste covers all textiles discarded at the end of their service life. These two categories of waste are briefly reviewed later.

6.6.3.1 Preconsumer waste

Using the current technology, preconsumer fiber waste is inevitable. In cotton fiber-to-yarn manufacturing, a significant amount of waste is produced as a result of the high percent of nonfibrous materials in the incoming fiber bales [47,48]. In the traditional cotton fiber-to-yarn conversion process, a carded ring-spun yarn process will typically be associated with total waste ranging from 12% to 20%. A combed ring-spun yarn process will typically be associated with total waste ranging from 20% to 30%. This category of waste typically consists of nonfibrous materials such as trash, leaf, seed-coat fragments, and fiber fragments. At least 30% of this waste consists of good cotton fibers that can be reused or recycled using independent operations, and the remaining materials end up in the landfills. The use of open-end spinning typically results in lower waste (8%–15%) because this type of spinning is only used for carded yarns and it requires shorter processing in comparison with ring spinning. However, virtually, all open-end spinning waste ends up in landfills. For wool fibers, the production of worsted yarns is associated with 20%–30% waste, and the production of woolen yarns is associated with up to 40% waste.

Waste management must represent an essential element in the design of a sustainable process model. As indicated earlier, manufacturing waste is inevitable given the existing technology of processing fibers into yarns, fabrics, and end products. The current approaches of waste management during processing have been based on handling waste materials independently through either technological methods of recycling or total discarding into the landfills. Over the years, many recycling technologies have been developed to recover fibers from comber noil and gin motes. These are cotton wastes that have good percent of reusable fibers. Most cotton manufacturing waste, however, consists of fragmented fibers or very immature fibers that have no reuse value as textiles. Some attempts have been made to use cotton waste as potential resource for biogas. In 2002, researchers at the USDA Agricultural Research Service Cropping Systems Laboratory at Lubbock, Texas, were looking at innovative uses of cotton waste from the ginning process [49]. They evaluated a process to turn the waste into pellets that can be used as fuel for heating purposes and for animal feed. By adding a little cottonseed oil to the pellets, they noted that the heating value was increased to about 9000 BTUs per pound of pellets, which is more heat output than from most wood pellets. The study revealed that more work needs to be done in this important area.

Most synthetic fibers used in yarn manufacturing are associated with lower waste than natural fibers. During manufacturing, different types of synthetic fibers may be associated with different waste. In the case of polyester and nylon fibers, the amount of waste may range from 3% to 5%. These are mostly pure fibers coming from fly generation, fragmented fibers caused by the opening process, or fiber neps removed during carding. Recycling of synthetic fibers can be achieved mechanically or chemically using well-established technologies. The problem, however, is that a significant percent of polyester fibers is blended with cotton fibers during yarn manufacturing. The blending process can be achieved intimately either by blending cotton and polyester staple fibers or later during the drawing process by feeding polyester and cotton fiber strands into a drafting system where they are drawn together forming a cotton/polyester blend [47].

From a product design viewpoint, blending cotton and polyester fibers provides an excellent combination of two fibers that are different in their inherent attributes with the result being a combined functional characteristic reflecting the best attributes of each fiber type. From a process design viewpoint, recycling of fiber waste during manufacturing will require separation of these two fibers, which is a major challenge that continues all the way to postconsumer waste. The alternative option of ceasing to blend natural and synthetic fibers and dividing them into two separate categories of product is certainly not economically feasible, and it will result in a loss-loss outcome for both fibers. This is where a truly creative process model and innovative technology are needed to allow blending of different fibers, while allowing separation of fibers. As impossible as this idea may seem, nothing is impossible in the engineering world. One positive step toward creating this technology is to move away from fiber blending during yarn manufacturing and delay it to the fabric manufacturing stage where yarns made from different fibers are woven or knitted together to provide a chance to separate these yarns in a deknitting or an unraveling process. Another option of handling

manufacturing waste is to move the recycling process to the main manufacturing line to allow simultaneous and efficient use of recyclable fiber waste either independently for lower-quality products or through blending waste fibers with virgin fibers. Many companies have been reluctant to take this approach for fear of the effects of waste facilities in terms of air pollution and contamination on the main manufacturing line. However, investments in tightly controlled waste handling facilities have proved to be effective in this direction, and some companies have been blending virgin and waste fibers at optimum levels to meet the desired yarn and fabric quality levels. In recent years, the author worked with a company in which fiber wastes were obtained by shredding cotton/polyester greige fabrics and blending the fibers produced intimately with the virgin cotton/polyester fiber blend to produce fancy yarns and nonwoven structures. This diversified business strategy has been very profitable for this company.

During weaving, fiber waste in the form of yarns for all types of fibers can reach up to 8% depending on the type of weaving preparation and the weaving process used [47,48]. The knitting process will typically be associated with less yarn waste (up to 4%). Garment manufacturing of knit and woven fabrics can be associated with a wide range of waste from 5% to 20% depending on the processes of cutting and sewing used. A great deal of waste during fabric and garment manufacturing can be a result of poor housekeeping and the lack of awareness of the importance of waste reduction. In textile manufacturing, a significant amount of waste can also be attributed to the current processing models and the logistical aspects associated with beam doffing and quality inspection. In the garment industry, the know-how still represents a key factor in reducing cutting and sewing waste.

6.6.3.2 Postconsumer waste

Postconsumer waste of textiles represents another significant source of waste that is highly unpredictable but on a continuous rise [50–52]. The data are truly staggering; according to the US Environmental Protection Agency (EPA) report in 2015 (https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/textiles-material-specific-data), US textile wastes generated in 2015 were 16 million tons. This was about 6.1% of the total municipal solid waste (MSW). The recycling rate for all textiles was 15.3% in 2015, with 2.5 million tons recycled. The total amount of textiles in MSW combusted was 19% in 2015, with 3.1 million tons combusted, and landfills received 66%, with 10.5 million tons of MSW textiles. These trends have been persistent since 1980, and they clearly indicate that more efforts must be made by municipalities, charities, and private collectors to collect clothing acceptable for reuse. In addition, more logistical infrastructure is needed for recycling methods. Currently, few business organizations are involved in the United States and Europe to distribute used clothing to poor countries in Africa and Asia. Postconsumer wastes are sorted by "rag graders" to determine the extent of their reusability. Wastes are typically separated manually depending on the fabric, fibers, and the quality or condition leading to sorting clothing into wearable and nonwearable textiles.

Recycling can be achieved by extracting fibers from fabrics using mechanical shredding. The problem with this process is that the fibers produced are typically very short and cannot be reprocessed into yarns and fabrics. To overcome this problem, recovered fibers may be blended with virgin fibers that act as carriers so that yarns can be spun. Another approach is to use the recovered fibers in making nonwoven structures that can be produced from short fibers. In recent years, many textile companies have implemented innovative recycling technologies of fiber waste. For example, some companies used fibers obtained from shredding fabrics in producing nonwoven structures that are suitable for making different types of products such as blankets and insulation materials. Other companies used fibers from shredded denim fabrics bonded together with synthetic materials to produce nontextile products such as work surfaces and plates. Recycling can also be achieved using chemical methods. Cellulose-based fibers like cotton and linen can be dissolved, and synthetic fibers can be melted and depolymerized. Blended fibers still represent a technological challenge; however, research by Hong Kong Research Institute of Textiles and Apparel (HKRITA) and sponsored by the Swedish H&M may soon result in positive results in this direction.

The earlier brief overview of waste management clearly indicates that there are many options that can be taken to prolong the life cycle of textile products. These include (a) minimization of manufacturing waste; (b) reutilization of manufacturing waste; (c) mechanical shredding of postconsumer products; (d) chemical recycling using pyrolysis and hydrolysis processes to convert oil-based fibers into basic chemicals, monomers, or fuels; (e) burning fibrous solid waste to generate heat; and (f) reusing textile products in its original form through distribution of affluence. The first five options are technology oriented, satisfying the *T*-factor in the IPAT equation, and the last option is affluence related, satisfying the *A*-factor in the IPAT equation. However, there are many key challenges associated with each approach as summarized in the points later:

(1) Minimization of manufacturing waste requires an integrated innovative technology in which incoming fibers are less prone to waste creation. For example, the cotton ginning process should aim at producing virtually pure cotton fibers free of trash particles and contaminants, and spinning technology should aim at smoothly process fibers with minimum fiber damage and fiber knots or neps.
(2) Reutilization of manufacturing waste should be integrated into the main manufacturing line as described earlier to avoid difficulties of fiber separation and efficiently manage the blend ratio of recycled and virgin fibers.
(3) Mechanical shredding of postconsumer products should be based on finding new products including nontextiles in which extracted fibers can be used.
(4) Chemical recycling should be made at minimum gas emission and energy use.
(5) Burning fibrous solid waste to generate heat should be based on minimum air pollution and health hazard issues.
(6) Reusing textile products in its original form is perhaps the most realistic option provided that logistical issues can be overcome.

In addition to the earlier options, there are many other creative approaches that can be taken to minimize fiber waste. For example, the textile industry needs to take a

closer look at a huge product category in the industry, that is, disposable textiles (wipes, diapers, feminine hygiene products, etc.). A substantial percent of these products is made of nonbiodegradable synthetic fibers and over 90% of these products end up in landfills. Carpets represent another product that is very difficult to recycle. Interface Inc. has developed a way to overcome this problem through leasing commercial carpets to business buildings and hotels for a certain period after which carpets are returned to the company to be reprocessed. This is a very creative approach since not only it assures an extended product's life but also it reduces the use of 100% virgin fibers since postconsumer products in this case become an integral element of raw material. Worldwide, estimates of discarded carpets amounted to about 8 million tons in 2018. Countries in Europe and other parts of the world have banned carpet from landfill, and many carpet recycling plants have ceased to operate due to a lack of raw materials. If these trends continue, the future of carpet being a consumer product will largely be threatened particularly in view of the many flooring alternatives available today.

6.6.3.3 The circular-economy process

The concept of providing service in the form of a product is perhaps the most intriguing concept of sustainability. This concept was pioneered by giant companies including Interface Inc., Caterpillar Inc., and Michelin tires. It is based on providing products to consumers in the form of continuous service. In simple words, it is about selling the same product repeatedly in the form of leasing a product to the consumer for use in a prespecified period dependent on the expected high-performance service life. During this period, product maintenance is the responsibility of the provider. Upon completion of this period, the product returns to the provider where it can be reprocessed again into a new product. Interface Inc. provides this service in its commercial tiles; Michelin provides this service to commercial transportation and airplane companies, and Caterpillar Inc. leases its construction equipment. This approach is fundamentally different than the current approach of linear manufacturing-based approach (the take-make-dispose production model) as it has become known as "circular economy [27]." The benefits of circular-economy production include minimum use of natural resources since used products become an integral element of raw material, virtually zero postconsumer waste, minimum use of energy particularly in manufacturing synthetic fibers that consume substantial energy in its production, lower manufacturing cost, and more use of skilled manpower by virtue of the rising learning curve.

Circular-economy manufacturing is an ongoing success story in the sustainability world. It is gaining increasing support from governments, business organizations, and consumers. However, it is still at its infant stage, and many challenges are yet to be overcome including the availability of innovative technologies that can integrate used materials with virgin material while preserving the integrity of end product, the inevitable deterioration in raw material quality and performance upon repeated processing, the number of times a certain material can be reused before it finally becomes totally unreusable, and other issues associated with reverse logistics.

6.7 Design thinking and lean-startup design

A sustainable process model should be based on a complete transparency of the process under consideration. This will require a continuous consultation with the company's users of services and products. Indeed, many of the solutions leading to sustainable developments stem from consumer's cooperation. The revolutionary approaches taken by companies that follow the circular-economy approach would not have come to reality without direct communication and coordination with consumers. This is particularly true given the need for a change in consumer's supply and demand cultures so that significant progress in sustainable development can be achieved. The affluence effect in the IPAT equation is perhaps the most dominant factor influencing sustainability today. In today's globalization trends, consumption of products must be designed in and not dictated upon consumers.

It is important, therefore, that the textile and garment industry seek new approaches of design conceptualization. There are many existing engineering approaches that can benefit the industry including "design thinking" [53–55] and "lean startup" [56]. Design thinking begins with the consumer by empathizing or observing people using an existing product and evaluating their views of product performance and the problems they encounter with the product. The outcome of the empathizing stage is then used to define or redefine the design problem. Once the idea is defined in view of consumer's experience, different ideas of meeting consumer's needs of a product should be entertained in the so-called ideate stage. Different ideas will simply mean implementing iterative process in which a cycle of ideate-prototype-testing is repeated until optimum performance is reached.

Lean-startup design is a human institution designed to create a new product or service under extreme uncertainty [56]. The principle of lean-startup design is like that of lean manufacturing discussed in Chapter 3, but it is implemented in the design phase with the goal being to reduce or eliminate waste and increase value-producing practices. The key elements of lean startup include minimum viable product (MVP), build-measure-learn, actionable metrics, and the assumption that good design is one that changes customer behavior toward a new ideal. MVP is about collection of maximum validated information about a product with the least effort and least cost. A company may assume that some added features may be appealing to potential customers; the company can then make small modification by adding minimal features to a product to test customer's response before a full-blown product is designed.

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Material selection

7

7.1 Introduction

In the previous chapters, key engineering aspects were discussed including product development, design conceptualization, design analysis, and design for sustainability. All these aspects have one critical factor in common, which is the selection of appropriate raw material. Many design problems are solved either by selecting raw materials of better attributes or by changing the type of material used. Since raw material makes up the building blocks of all manufacturing processes, the choice of one raw material versus another could mean substantial cost reduction. This point is very common in textile technology in which manufacturing cost is often minimized by the choice of an appropriate fiber type or blending fibers of different prices at predetermined ratios and under quality constraints.

Functional characteristics and structural features of products are largely determined by the type and properties of raw material. Common properties considered in the selection of raw material include [1, 2] (a) mechanical properties (e.g., strength, stiffness, ductility, hardness, and toughness), (b) physical properties (e.g., density, thickness, weight, electrical conductivity, and thermal resistance), (c) chemical properties (e.g., composition, reactivity, degradability, absorption behavior, and toxicity), (d) manufacturability (e.g., integrity, pliability, formability, and compatibility), and (e) reusability and recyclability (e.g., extent of material separation, reformability, and after-use properties). The availability of a wide range of materials and processes in today's technology has led to the design of products that exhibit many advantages including light weight, energy efficient, durability, color and texture variety, thermal resistance, conductivity, abrasion resistance, and dye and moisture absorption.

In this chapter, basic steps of material selection will be discussed. These are critical steps that can assist in making decisions regarding the selection of material. The discussion will then be shifted to a review of the key tasks of evaluating material candidates for a certain product. These include (a) knowledge of the common material categories (i.e., screening category), (b) understanding basic material properties (i.e., screening property), (c) determining the optimum cost of material with respect to its performance and its contribution to the value of the end product, (d) understanding the effects of technology on material selection, and (e) understanding the differences between design-direct and value-impact performance characteristics. Many examples of fibrous materials are presented in the context of these tasks.

7.2 Basic steps of material selection

Material selection being a key element of the design cycle should primarily be driven by the design problem statement [1, 2]; this is the starting point of any material selection process as shown in Fig. 7.1. In this regard, the problem statement should

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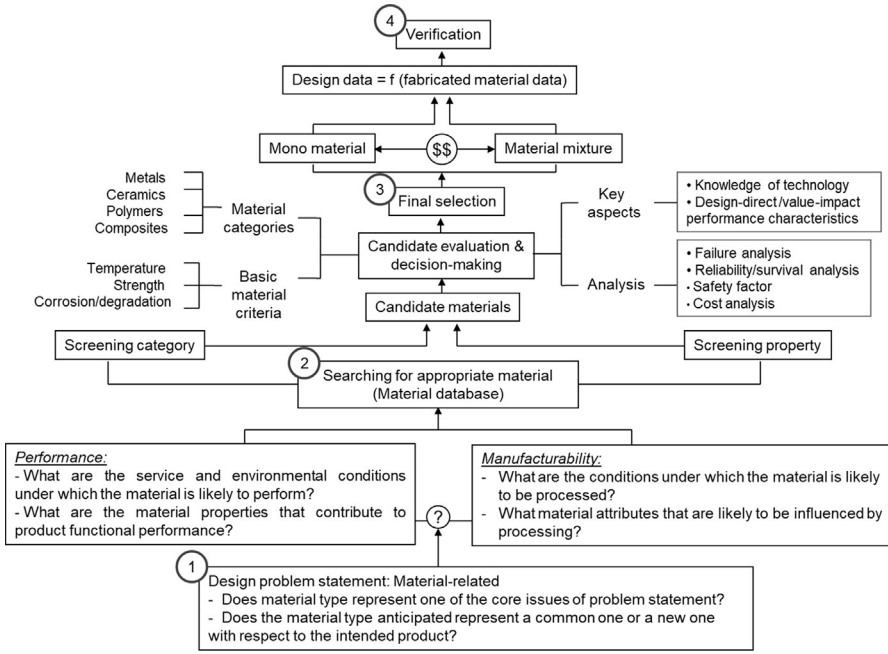


Fig. 7.1 Basic material selection steps.

address two key questions: (a) Does material type represent one of the core issues of the problem statement? (b) Does the material type anticipated represent a familiar one or a new one with respect to the intended product? In some situations, the core issue of the design problem is the type of material needed to achieve better performance or prevent product failure. This situation is common with existing products that do not perform well under some circumstances due to some inherent limitation in material characteristics. For example, if the design problem is carpet stain propensity, a polypropylene or polyester fiber will provide a good choice of raw material because of their low absorption of stain particularly water-based staining materials [3, 4]. On the other hand, if the design problem is primarily durability and resilience, wool and nylon will provide better options. It is also important not to confuse design problems associated with raw materials and those associated with construction. For example, some of the common safety issues of carpets are dust collection, poor indoor air quality, and allergens particularly with consumers who suffer symptoms with asthma and allergies. This is primarily a carpet construction problem and not material related. Certainly, modification of fiber surface using dust resistance surface treatment can assist in solving the problem [5]. More on the selection of materials for carpets will be discussed in Section 7.7.1 of this chapter.

In other situations, material selection may represent a straightforward process by virtue of the limited options of available appropriate materials or the well-established

performance of current materials used for the product in question. For example, the most commonly used material for denim jeans, which has been used since the 19th century, is cotton fiber. This is a direct result of the fact that denim fabric derives its familiar texture and desired appearance from the nature of cotton fibers. However, this does not exclude attempts to use alternative fibers or add other fiber types to cotton for specific fashionable effects or performance applications. Indeed, denim fabrics have been made from blends of cotton with other fiber types such as flax and polyester. Denim fabric has also been made from regenerated cellulose fibers such as TENCEL fiber. However, fiber splitting during yarn dyeing and fabric finishing has been a problem that needs to be resolved before this type of fiber can find its fare market share in the denim business. In technical textiles, some fibers dominate the markets of some products because of their unique attributes in relation to product performance characteristics. For example, nylon 6,6 fiber is the dominant material used for safety airbags due to its superior capability in energy absorption, heat resistance, and stability over time as will be discussed later in this book.

In view of the design problem statement, material selection may proceed using the basic steps shown in Fig. 7.1. The two key factors that should be taken into consideration are material performance and material manufacturability. The former reflects product performance, and the latter reflects the ease of processing and manipulation of materials into the desired product construction. In relation to product performance, the key questions to be addressed are as follows: (a) What are the service and environmental conditions under which the material is likely to perform? (b) What are the material properties that contribute to product functional performance? These questions are normally specific to the type of end product designed and its intended functions. In relation to material manufacturability, the key question will be as follows: What are the conditions under which the material is likely to be processed? What material attributes are likely to be influenced by processing? These questions are largely determined by the type of manufacturing used (i.e., mechanical or thermal) and the extent of stresses or heat associated with material processing. For example, processing of fibers during spinning requires a great deal of mechanical stresses in which fibers are repeatedly subject to different modes of deformation [6]. In this case, elasticity, resilience, and interfiber friction can be considered as key fiber properties associated with processing propensity.

The next basic step of the material selection process is searching for material candidates suitable for the intended product in view of the questions addressed in the first step. Searching for appropriate raw materials involves two key common terms among engineers [1, 2, 7]: screening category and screening property. Screening category is the best type of material (or material blend) that is suitable for the product in question. Screening property is any material property for which an absolute lower (or upper) limit can be established for the application. Both screening category and screening property of materials require the availability of database, which emphasizes the role of science discussed in the previous chapters. Without a reliable database, a material selection process can be lengthy and costly. Database should include both traditional and nontraditional materials as this provides the design engineer with a more global view of all material options and alternatives.

The search process should result in a set of material candidates that have great potentials to meet the desired product performance and manufacturing criteria. The next step is to evaluate the candidate materials more closely so that a decision can be made about the best material category, material type, and material properties for the design application in hand. In situations where a new product is being developed or when limited information is available about past material performance, more in-depth analysis should be made, supported by extensive testing of relevant material characteristics. This is where joint efforts between scientists and engineers will be needed.

Evaluation of candidate materials is a highly variable practice that depends on many factors including the complexity of the product, the extent of prior knowledge of material performance, the clarity of material contribution to the product, and the cost of material. In general, traditional products are typically associated with familiar materials and high predictability of their performances. New products or highly technical products will be more complex than traditional products by virtue of the high specificity associated with their performance. As a result, they may require continuous development and ongoing search for more advanced materials to satisfy and improve specific functions. The clarity of material contribution to the product is a critical aspect of material evaluation that requires specific tasks including understanding the relative merits of using one material over another and evaluating basic material criteria such as temperature resistance, strength, and corrosion or degradation behavior. In addition, some analyses associated with determining the appropriateness of material for a certain product may be necessary. These include failure analysis, reliability and survival analysis, and safety factors [7]. In addition, material cost is often a major factor in selecting the appropriate material for a certain product. This is particularly true in engineering textiles since raw material cost may reach up to 70% of the total manufacturing cost [6].

The outcome of the material selection process may be represented by the choice of a single material with associated characteristics or two or more materials that can be mixed together to meet the desired application. In either case, it will be important to evaluate design data properties. These are the properties of the selected material in its fabricated state. The need for knowledge of these properties stems from the fact that a material in isolation could have a substantially different performance than that exhibited by the same material in a product assembly. This point is particularly true with fibrous products. Indeed, it is well established that as fibers are converted into different structures (yarns or fabrics), some of their characteristics can be altered in their magnitudes and in their relative contributions to end-product performance [8, 9]. Knowledge of material design properties can be based on long experience with existing products, reliable database, or extensive testing that aims at simulating material performance in fabricated forms.

In view of the earlier discussion, the key tasks of evaluating material candidates for a certain product are (a) knowledge of the common material categories (i.e., screening category), (b) understanding basic material properties (i.e., screening property), (c) determining the optimum cost of material with respect to its performance and its contribution to the value of the end product, (d) understanding the effects of

technology on material selection, and (e) understanding the differences between design-direct and value-impact performance characteristics. These tasks are discussed in the following sections.

7.3 Material categories

Over 95% of available materials consist of four main categories: metals or metal alloys, ceramics, polymers, and composites. The key factor in this categorization is material structure. In other words, each one of these four categories of material exhibits structural features that make it uniquely distinguished from the other categories in both properties and applications. In general, material structure can be divided into four levels: atomic structure, atomic arrangement, microstructure, and macrostructure [2, 10]. The role of conventional design is typically to understand and manipulate both the microstructure and the macrostructure of material. However, the atomic and crystal structures of materials must be first understood to allow such manipulation.

The importance of understanding the atomic structure of materials stems from the fact that materials are essentially made up from atoms. Although there are only about 100 kinds of atoms in the universe [10], how they are put together is what makes a certain material form trees or tires, ashes or animals, and water or air. They are all made from atoms many of which are used several times. In general, the atomic structure influences how the atoms are bonded together, which in turn provides specific ways to categorize materials as metals, ceramics, or polymers. This permits exploratory analysis of the mechanical properties and the physical behaviors of these different material categories. Fundamentally, the atom consists of a nucleus containing neutrons and protons around which electrons orbit in more or less confined radii [2, 10]. The smaller the diameter of the orbit, the greater the attractive force between the electron and the nucleus and the greater the absolute binding energy. The innermost orbit will exhibit a large binding energy, and the electrons in the outer orbits are bound less tightly. Indeed, the outermost electrons may be considered as loosely bound and not necessarily residing in well-defined orbits. These are the so-called valence electrons and are the ones that are involved in the bonding together of the atoms and hence strongly affect all material properties: physical, mechanical, and chemical. The nature of this bonding is what determines whether the substance is a metal (bonds between like atoms) or a ceramic or a polymer material (bonds between dissimilar atoms).

In the following sections, the main categories of material are briefly reviewed. The discussion will be restricted to examples of materials within each category, their important structural features, and general applications that are suitable with respect to material capabilities. Each material category deserves many books to be fully covered. However, the objective of reviewing these categories of material is to provide polymer and fiber engineers with generalized concepts of material categories with the hope of attracting them to read more about these materials in highly specialized literatures.

As indicated earlier, metals, ceramics, polymers, and composites represent the main categories of material. In addition, other types of materials may also be identified based on their unique characteristics. These include wood, foam, and porous ceramics. As an aid to the discussion given later, the reader should refer to Figs. 7.2–7.6 as they illustrate some of the main differences between the major categories of materials. These figures represent simplified versions of Cambridge material charts [11], verified by other sources of material information [1, 2, 10]. Note that in Figs. 7.2–7.5, yield strength under tension is the one considered for all materials, except for ceramics for which yield strength under compression is considered. The reason for using this parameter is that ceramic tensile strength is typically about 10% of its compressive strength.

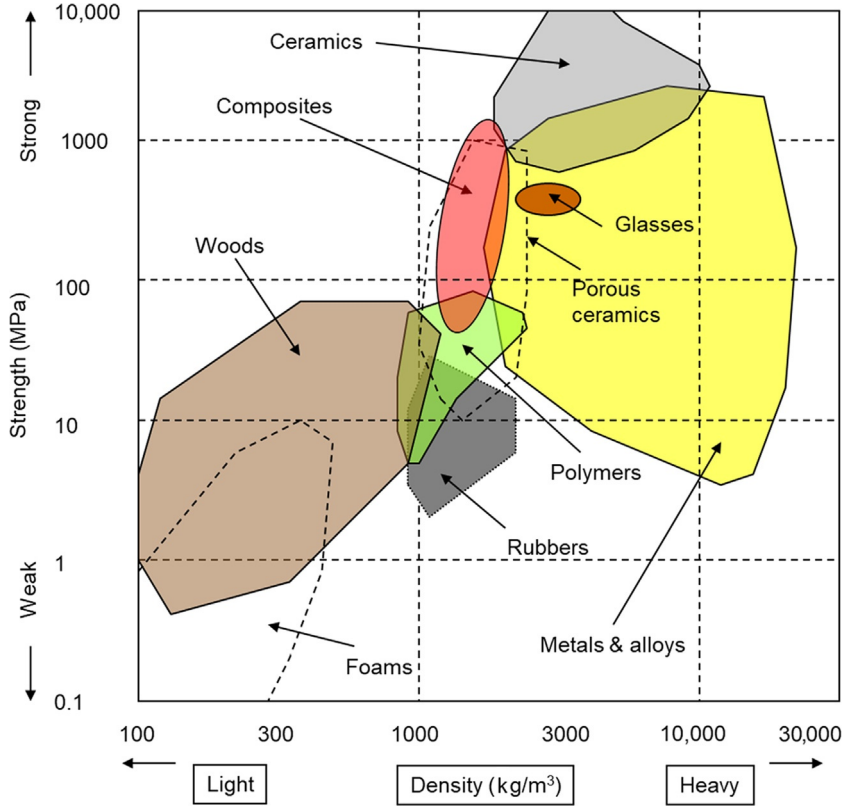


Fig. 7.2 Yield strength-density of major material categories.
Modified from Cambridge Material Charts, Department of Mechanics, Materials, Design, United Kingdom, 2002. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts.

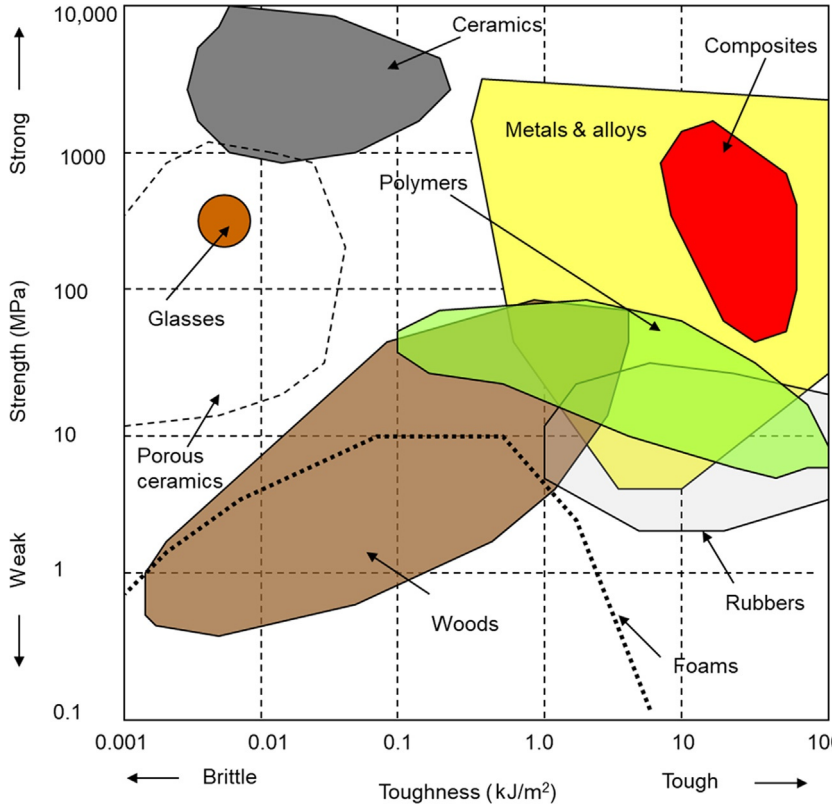


Fig. 7.3 Yield strength-toughness of major material categories.
Modified from Cambridge Material Charts, Department of Mechanics, Materials, Design, United Kingdom, 2002. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts.

7.3.1 Metals and metal alloys

Among the four main categories of material, metals are the oldest materials as they have been used for hundreds of years in numerous products including appliances and auto bodies (low-carbon sheet steels), cutlery and utensils (stainless steels), aircraft frames and surfaces (aluminum alloys), and electrical wiring and water pipes (unalloyed copper). Metallic materials are mainly inorganic substances composed of one or more metallic elements, but they may also contain nonmetallic elements. An important classification of metals is ferrous versus nonferrous category [10, 12]. For ferrous metals, the primary metallic element is iron (e.g., alloy steel, carbon steel, cast iron, and wrought iron). These metals are valued by their tensile strength and durability. Carbon steel (also known as structure steel) is essential in the construction industry and is used in skyscrapers and long bridges. Ferrous metals are also used in shipping containers, industrial piping, automobiles, railroad tracks, and many commercial and domestic tools. Ferrous metals have a high carbon content that

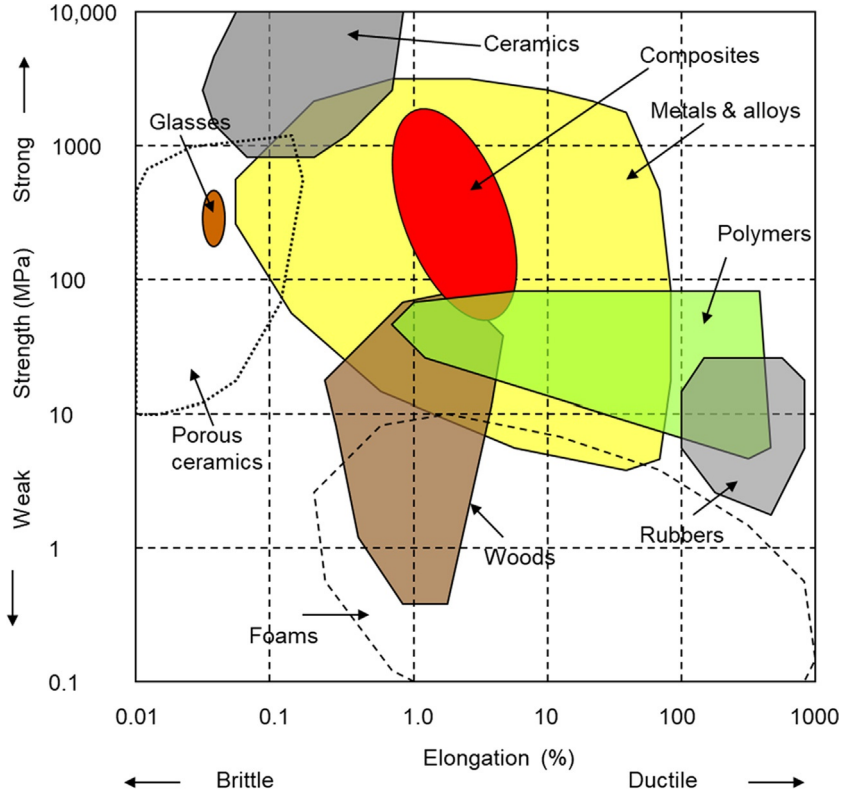


Fig. 7.4 Yield strength-elongation of major material categories.
Modified from Cambridge Material Charts, Department of Mechanics, Materials, Design, United Kingdom, 2002. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts.

generally makes them vulnerable to rust when exposed to moisture. The two exceptions to this rule are wrought iron that resists rust due to its purity and stainless steel that is protected from rust by the presence of chromium [12]. Most ferrous metals are magnetic, which makes them very useful for motor and electrical applications. Nonferrous metals, on the other hand, may contain elements other than iron (e.g., copper, aluminum, nickel, titanium, and zinc) and precious metals like gold and silver. Their main advantage over ferrous materials is their malleability [12]. They also have no iron content, giving them a higher resistance to rust and corrosion and making them ideal for gutters, liquid pipes, roofing, and outdoor signs. They are also nonmagnetic, which is important for many electronic and wiring applications.

A metallic structure is primarily a crystalline structure consisting of closely packed atoms arranged in an orderly fashion [1, 2, 10, 12]. This provides metals with good light reflectance and high density in comparison with other materials as shown in Fig. 7.2 and with their familiar high strength and exceptional toughness in comparison

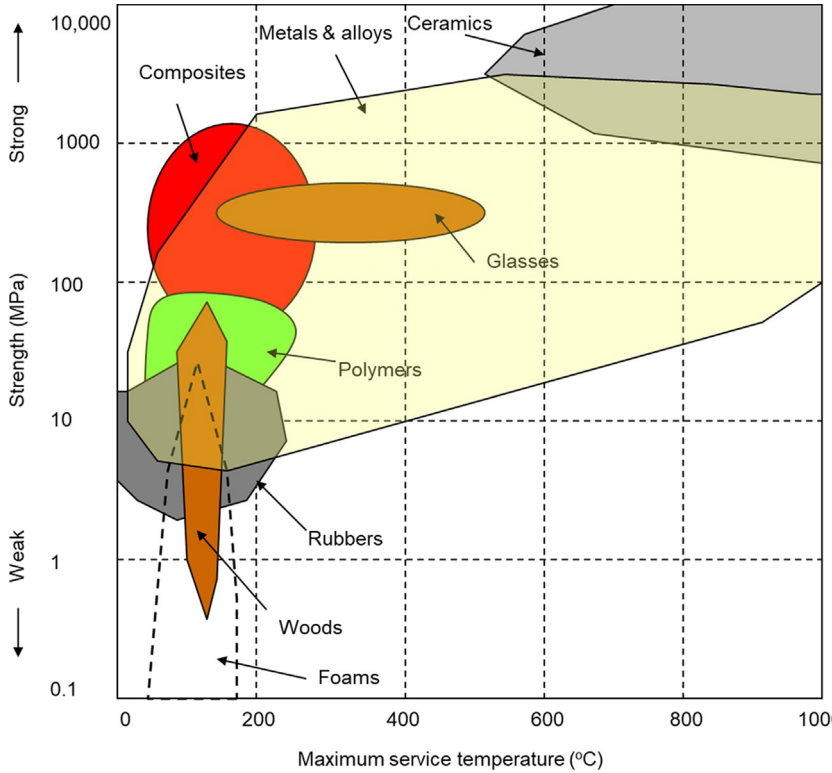


Fig. 7.5 Yield strength-temperature of major material categories.
Modified from Cambridge Material Charts, Department of Mechanics, Materials, Design, United Kingdom, 2002. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts.

with most other materials as shown in Figs. 7.2–7.4. The high strength of most metals is largely maintained at elevated temperatures as shown in Fig. 7.5. Other mechanical properties of metals, such as hardness, fatigue strength, ductility, and malleability, are largely influenced by the presence of defects or imperfections in their crystal structure. For example, the absence of a layer of atoms in its densely packed structure enables a metal to deform plastically and prevents it from being brittle [12].

Metals are commonly alloyed together in the liquid state so that, upon solidification, new solid metallic structures with different properties can be produced. In addition, metals are typically manufactured in their nearly final shape (e.g., sheet ingots or extrusion billets) through a casting process in which metals and alloys are cast into desirable geometries [12]. Products in this form are commonly called castings, and they can be subsequently worked using common processes such as rolling and extrusion into fashioned or wrought products (e.g., sheets, plates, and extrusions).

Metals are also good electrical conductors as shown in Fig. 7.6. They are also good thermal conductors. The high electrical and thermal conductivities of simple metals

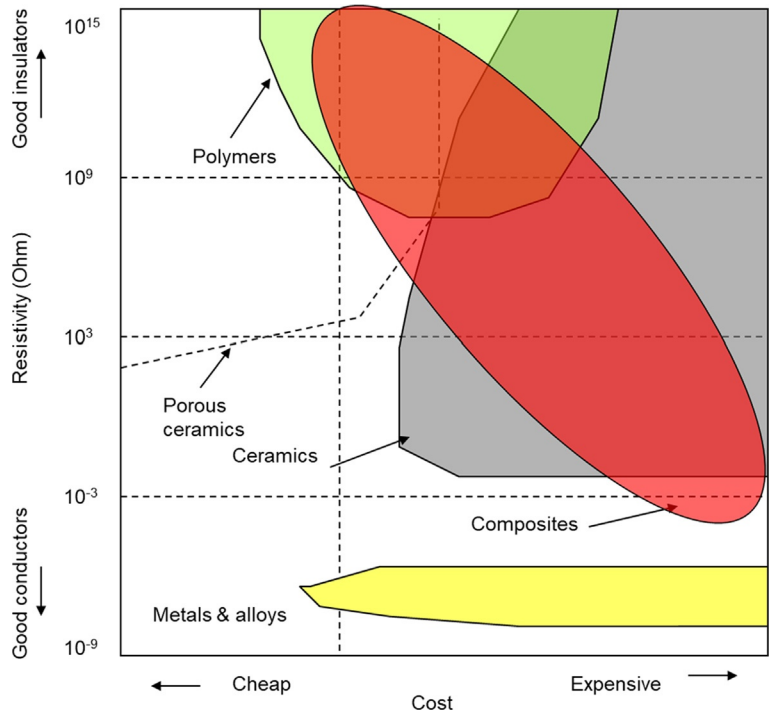


Fig. 7.6 Electrical resistivity versus estimated cost of different materials. Modified from Cambridge Material Charts, Department of Mechanics, Materials, Design, United Kingdom, 2002. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts.

are best explained by reference to the free-electron theory [1, 2], according to which the individual atoms in such metals have lost their valence electrons to the entire solid, and these free electrons that give rise to conductivity move as a group throughout the solid. In the case of complex metals, conductivity is better explained by the band theory, which takes into account not only the presence of free electrons but also their interaction with the so-called *d* electrons [1, 2, 12].

7.3.2 Ceramics

Ceramic material is essentially a combination of one or more metals and nonmetallic substance chemically bonded together [1, 2]. For this reason, they are often defined as inorganic nonmetallic materials and classified according to the nonmetallic element such as oxides, carbides, nitrides, and hydrides depending on whether the metal is combined with oxygen, carbon, nitrogen, or hydrogen. In contrast with most metals, ceramics can be crystalline, noncrystalline, or mixtures of both. They exhibit high hardness and high strength at elevated temperatures (see Fig. 7.5). However, the biggest flaw that hinders their widespread use in various applications is brittleness and

propensity to crack propagation [10, 11]. They also have medium to high electrical insulation as shown in Fig. 7.6. Furthermore, their melting points are significantly higher than those of metals, and they are much more resistant to chemical attack. These features make ceramics useful for electrical and thermal products of high insulation.

Ceramic materials can generally be categorized into three main categories [1, 2, 10]: (a) conventional ceramics, (b) advanced or technical ceramics, and (c) glasses. Conventional or traditional ceramics consist of three basic components: clay, silica, and feldspar. Clay is a form of ceramic before hardening by a firing process, and it makes up the major body material. It consists mainly of hydrated aluminum silicates ($Al_2O_3 \cdot SiO_2 \cdot H_2O$) with smaller amounts of other oxide impurities. The silica (SiO_2) has a high melting temperature and provides the refractory component of traditional ceramics. Feldspar ($K_2O \cdot Al_2O_3 \cdot 6H_2O$) has a low melting temperature and produces a glass when the ceramic mix is fired; it bonds the refractory components together. Advanced or technical ceramics are typically pure or nearly pure ceramic components or mix of components. They are normally of higher price because of the necessary control required to produce them. Examples of advanced ceramics include aluminum oxide (Al_2O_3), zirconia (ZrO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), and barium titanate ($BaTiO_3$). Common applications for advanced ceramics include alumina for auto spark-plug insulators and substrates for electronic circuitry, dielectric materials for capacitors, tool bits for machining, and high-performance ball bearings. The third category of ceramics is glasses, which are different from all other ceramics in that their constituents are heated to fusion and then cooled to a rigid state without crystallization [2]. The solid form of silica is a glass with SiO_2 being the main glass ingredient, but it is still a noncrystalline ceramic material.

The choice of ceramic materials in engineering design is due to many key functional characteristics. These include heat resistance, great hardness and strength, considerable durability, low electrical and thermal conductivity (good insulators), chemical inertness (unreactive with other chemicals). Most ceramics are also nonmagnetic materials, although ferrites (iron-based ceramics) happen to make great magnets (because of their iron content). Major drawbacks of ceramic materials include fragileness and brittleness.

7.3.3 Polymers

Polymers are mainly carbon-containing long molecular chains or networks [13]. Interestingly, they are known in public as plastics, a term that typically defines materials that can be easily molded. Although most polymeric materials are noncrystalline or partially crystalline, some can be made of highly crystalline structures. As a result, some polymeric materials can be found in a wide range of strength and toughness that overlap with some metals as shown in Figs. 7.3–7.5. In addition, some are highly ductile, and many are moisture absorbent. As shown in Fig. 7.2, most polymers have lower densities than metals and ceramics. They also have relatively low softening

or decomposition temperature, and many are good thermal and electrical insulators as shown in Fig. 7.6.

In general, polymeric materials can be classified into three classes [1, 2, 13]: (a) thermoplastics, (b) thermosets, and (c) elastomers. Thermoplastic polymers consist of very long chains of carbon atoms strongly (covalently) bonded together, sometimes with other atoms, such as nitrogen, oxygen, and sulfur, also covalently bonded in the molecular chains. In addition, weaker secondary bonds bind the chains together into a solid mass. It is those weak bonds that make thermoplastic polymers soften under heat, forming a viscous state that allows geometrical and shape manipulation of this material. Solidifying or setting these conditions via cooling into rigid solid states will result in retaining their shapes and geometries. Examples of thermoplastic polymers include [13] polyethylene, polyvinyl chlorides, and polyamides. Products generated from these polymers include plastic containers, electrical insulation, automotive interior parts, appliance housings, and fibrous materials.

Thermosets are polymeric materials that do not have long-chain molecules, instead a network of mainly carbon atoms covalently bonded together to form a rigid solid. Again, nitrogen, oxygen, or other atoms can be covalently bonded into the network. Thermosets are typically manipulated to form shapes and geometries and then cured or set using chemical processes that involve heat and pressure. Once they are cured or set, they cannot be remelted or reshaped into other forms [1, 13]. The common product application for thermosets is matrix substance for fiber-reinforced plastics (e.g., epoxy).

Elastomers are long, carbon-containing molecular chains with periodic strong bond links between the chains. As the name implies, elastomers (commonly known as rubbers) can easily deform elastically when subjected to a force and can recover perfectly to their original shapes upon removing the force. They include both natural and synthetic rubbers, which are used for auto tires, electrical insulation, and industrial hoses or belts.

7.3.4 Composites

Composite material is not inherently a single category of material as it is made from a mixture of two or more materials that differ in form, structure, and chemical composition but are essentially insoluble in each other [1, 2]. Most fiber composites are produced by combining different types of fibers with different matrices for the purpose of meeting specific performance criteria such as strength, toughness, light weight, and thermal stability. The basic idea is simple; while the structural value of a bundle of fibers is low, the strength of individual fibers can be boosted if they are embedded in a matrix that acts as an adhesive to bind the fibers and lend solidity to the overall structure. The matrix also plays a key role; it protects the fibers from environmental effects and physical damage, which can initiate cracks. Both the fibers and the matrix combined act together to prevent structural fracture [14, 15]. In contrast to composites, a monolithic (or single) material may suffer fracture that can easily propagate until the material fails.

Materials considered for composite matrices include [10–15]: polymers, metals, and ceramics. The most common type is polymeric-matrix composites. This can be found in applications under temperatures up to 200–400°F. One of the earliest types of polymeric-matrix composites was glass-fiber composite in which short glass fibers are embedded in a polyester plastic matrix to form a lightweight structure suitable for many applications including appliances, boats, and car bodies. In addition to light weight, this type of composites also exhibited many important features such as ease to fabricate in different shapes, corrosion resistance, and moderate cost [14]. Other polymeric-matrix composites include carbon and aramid fibers embedded in heat-resistant thermoset polymeric matrices [1, 2, 14]. These have been used in many applications such as aircraft surface material and structural members. Metal-matrix composites are fabricated by embedding fibers such as silicon carbide and aluminum oxide into aluminum, magnesium, and other metal alloy matrices. The role of fibers here is to strengthen the metal alloys and increase heat resistance. These types of composites are commonly used for automotive pistons and missile guidance systems [14]. Ceramic-matrix composites include the reinforcement of alumina with silicon carbide whiskers. These are used to enhance the fracture toughness of ceramics.

The structure and shape of fiber composites vary greatly depending on the application and the direct purpose for which the material is used [1, 2]. In general, the most effective approach to form composite structures is by using long fiber strands employed in the form of woven structures, nonwoven structures, or even layers of unidirectional fibers stacked upon one another until a desired laminate thickness is reached. The resin may be applied to the fibrous assembly before laying up to form the so-called prepregs, or it may be added later to the assembly. In either case, the structure must undergo curing of the net assembly under pressure to form the fiber composite. The way different components in a composite structure contribute to its properties is simply realized using the familiar rule of mixtures, which expresses the composite stress, σ_c, as follows [1, 2]:

$$\sigma_c = \sigma_f V_f + \sigma_m V_m$$

where σ_f is the strength of the fiber component, V_f is the volume fraction of fibers, σ_m is the strength of the matrix component, and V_m is the volume fraction of the matrix.

The rule of mixtures is analytically associated with many key criteria. The first criterion is that fibers must be securely bonded to the matrix in the sense that atoms of each component react and bond together. Different components also interact and bond together. In this case, the rule of mixture will still hold as long as the potential failure of the composite is unlikely to occur at the interface between the different components [2]. This assumption can be gross in some situations in which the interface represents the weakest region of the fiber composite. This is a design issue that must be handled through selection of appropriate materials and optimum fiber orientation. The second criterion is that the fibers must either be continuous or overlap extensively along their respective lengths. The third criterion is that there must be a critical fiber volume, $V_{f\text{-}critical}$ for fiber strengthening of the composite to be effective. The fourth criterion is that there must be a critical aspect ratio or a fiber length/diameter ratio for

reinforcing to occur. The detailed analysis of the rule of mixtures is outside the scope of this chapter, but they can be found in numerous literatures [1, 2, 14].

From a design viewpoint, engineers should realize that for optimum composite performance, not only the choice of appropriate fibers is important but also the way fibers are oriented and incorporated in the matrix. The latter is directly cost associated. One way to avoid expensive hand lay-up operations is to use nonwoven structures or chopped fibers that are arranged in mat form or use loose fibers that may be either blown into a mold or injected into a mold along with the resin. In choosing matrix materials, other challenges, or design problems, can be faced. These include [1] the choice of appropriate material (e.g., epoxies, polyimides, polyurethanes, and polyesters), processing cost, processing temperature (curing temperature if using a thermoset polymer and melting temperature if using a thermoplastic polymer), flow properties in the molding operation, sag resistance during paint bake out, moisture resistance, and shelf life. These multiple factors require full collaboration between fiber and polymer engineers and engineers of various fields in which composite structures are utilized.

7.4 Basic criteria of material

To make an appropriate decision about which material to select for a specific application, engineers should understand the basic criteria of material and the specific criteria required for the intended product. For existing products that require modification, this may be a simple task. For newly developed products, this task can be more complex. As G. T. Murray describes [1], "Often, more questions are raised than are answered and the engineer is not always aware of all the parameters required in the material selection process."

As indicated in the basic steps discussed earlier, engineers should begin by searching for a set of appropriate materials in view of the problem statement established and both manufacturing and performance criteria. Material candidates should be selected based on careful trade-off between many factors. Cost is a critical factor in selecting the appropriate material. However, this factor should not be considered as the first one in selecting the best material required for a specific design application, only after a list of candidate materials is selected based on their technical criteria that cost should be considered. For most design applications, these criteria include temperature, strength, and corrosion or degradation resistance. Key points associated with these criteria are discussed later.

7.4.1 Temperature

For applications where changes in temperature are inevitable, temperature will represent the most critical criterion in determining which material to select. For most materials, strength may deteriorate with the increase in temperature. In addition, oxidation and corrosion of material are likely to increase with temperature. Some categories of material are eliminated in applications involving elevated-temperature usage (above 500°C). These may include most polymers and low-melting point metals [10]. On the

other hand, design applications under room temperature or lower (e.g., −10 to 50°C) can be associated with thousands of potentially useful materials including polymeric materials [1, 2].

The importance of temperature in selecting a certain material has resulted in categorizing some materials as being high-temperature materials. These are materials that serve above about 1000°F (540°C). Fig. 7.5 illustrates plausible ranges of strength and maximum service temperature for the major categories of material. As can be seen in this figure, some metals and ceramic materials dominate the high-temperature applications. Specific materials known for their high-temperature applications include [12–15] stainless steel, austenitic superalloys, refractory metals, ceramics or ceramic composites, metal-matrix composites, and carbon or graphite composites. Even among these materials, the first three are well established in industrial applications, and the other materials are still under extensive research to determine whether they can be used as substitutes or extensions to the capabilities of austenitic superalloys in high-temperature applications such as aircraft jet engines, industrial gas turbines, and nuclear reactors.

When fiber is the material of choice, one will find that most conventional fibers decompose at temperatures below 300°C. The only inherently temperature-resistant fiber is asbestos (naturally occurring mineral fibers). This fiber does not completely degrade by high temperature. However, its extreme fineness makes it health hazard as it can be breathed into the human lungs. Glass fibers have been used as a substitute to asbestos fibers because of their high heat resistance (up to 450°C). Unfortunately, these fibers have poor aesthetic characteristics and high densities and can be difficult to process [14, 15]. Another fiber type that can be used for high-temperature applications is aramid fibers (e.g., DuPont Nomex and Teijin Conex). These are highly thermally resistant fibers as they char above 400°C and may survive short exposures at temperatures up to 700°C. The key characteristic of this type of fibers is that they can resist temperature of up to 250°C for 1000 h with deterioration in breaking strength of only 35% of that before exposure [16]. This makes them good candidates for fire protection or flame-retardant applications. Another fiber type that is basically a high-performance aromatic fiber made from linear polymers is the so-called PBO, or poly(p-phenylene benzobisoxazole) [17]. This type of fibers exhibits very high flame resistance and has exceptionally high thermal stability with the onset of thermal degradation reaching 600–700°C. They also have very good resistance to creep, chemicals, and abrasion. However, they exhibit poor compressive strength (they kink under compression), which restricts their use in composite structures.

7.4.2 Strength

Material strength is perhaps the most critical criterion in all design applications, as most products must have minimum acceptable durability to be able to perform properly and to prevent structural failure. In this regard, it is important to identify the specific type of applied stress that a product will encounter during use and the level of this stress. In most design applications, yield strength, stiffness, and toughness represent the key material strength parameters determining the product performance [10, 11].

In addition, the mode of stress should be realized including tension, compression, torsion, and bending [9]. Figs. 7.2–7.5 clearly demonstrate the differences in strength parameters between different material categories.

Typical questions related to strength in a design project include the following: (a) What is the maximum applied stress that is likely to be encountered during the manufacturing or the use of a product? (b) Can some plastic deformation or permanent set be tolerated? (c) Is the applied stress static or dynamic? (d) What is the pattern of dynamic stress (random or periodic)? In addressing these questions, engineers should have good knowledge of the strength properties of the specific material used in the design application. In addition, they should have a good grasp of the basic concepts of material strength. Table 7.1 provides definitions and criteria of some of the key strength parameters of material.

When fiber is the material of choice, the importance of strength stems directly from the type of application or the intended end product [8, 9, 15, 18]. Most fibers are essentially polymer-based materials, and they largely share many of the inherent

Table 7.1 Some strength-related parameters considered in material selection [1, 2, 11].

Strength parameter	General criteria
Yield strength	- The most critical strength parameter in design applications - It is often more critical than the breaking strength as a result of the permanent deflection that the material encounters when it is loaded with stresses exceeding its yield limit - For some materials, yield strength under torsion is smaller than that under axial tension
Flexibility or stiffness	- Flexibility is the ease to deform or change in dimension under applied stresses - Elastic modulus (Young's modulus) is used to measure the stiffness under tension. The higher the elastic modulus, the less flexible, or the stiffer the material - Stiffness under bending is measured by the flexural rigidity of material - Stiffness under torsion is measured by the torsional rigidity of material - All stiffness measures are largely constant for a certain material. Material inherent modulus cannot be altered without altering material composition or using special mechanical treatments (e.g., mechanical conditioning) - Flexural rigidity and the torsion rigidity are highly sensitive to material dimensions; they are proportional to d^4, where d is the diameter of circular material (e.g., rounded fiber or yarn) - For fibrous materials, specific modulus is typically expressed in terms of modulus/linear density ratio (e.g., g/denier or N/tex)

Table 7.1 Continued

Strength parameter	General criteria
	- For metals, the modulus of a soft metal is identical to that of the same strain-hardened metal - For polymers, the moduli are relatively very small and not well defined - Traditional fibers exhibit elastic modulus values in the range from 10 to 30 g/den; some industrial fibers can be in the range from 30 to 100 g/den. High-performance fibers can be much greater than that (from 300 to over 1000 g/den or 50 to 600 GPa) - Ceramics have the highest moduli under compression because of their strong covalent-ionic bonds - Composite materials can be made to a wide range of desired moduli
Ductility	- Ductility is the property of material that allows it to be formed in various shapes - In general, the higher the strength and the lower the elongation, the lower the ductility of the material - When both strength and ductility are design requirements, some compromise must be made - For metals, the strength can be increased significantly by reducing the grain size without a significant reduction in ductility - For composite materials, volume fraction, and components orientation can be adjusted to provide a wide range of desired ductility at minimum reduction in strength - Polymers exhibit wide variation in their ductility and glass temperature. As a result, more compromises must be made because of their relative weakness in comparison with other material categories - Ductile ceramic hardly exists - Brittle materials (e.g., cast iron, ceramics, and graphite) are generally much stronger in compression than in tension as tensile stress can cause crack propagation and compressive stress tends to close cracks
Toughness	- Toughness is the resistance to fracture of a material when stressed - It is typically defined by the energy (ft-lb) that a material can absorb before rupturing - Toughness can be a temperature/time sensitive parameter, particularly at elevated temperatures - It should be highly considered in applications involving shock or impact loading - Since this parameter is highly application oriented, no standard distinction between different material categories can be easily specified, and extensive testing should be made to realize the effectiveness of certain material under the application in question

characteristics of polymers. However, the unique structure of fiber being a long molecular chain provides many additional strength advantages that exceed those of conventional polymeric structures. This point will be clearly demonstrated in Chapter 8.

7.4.3 Corrosion and degradation

Corrosion resistance is the parameter that describes the deterioration of intrinsic properties in a material due to reactions with surrounding environments [19]. Corrosion occurs with the help of corrosive chemicals, solids, liquids, or gases that are capable of harming living tissues or damaging surfaces in contact. Corrosive chemicals include [1, 2] acids, bases (caustics or alkalis), dehydrating agents (e.g., phosphorous pentoxide and calcium oxide), halogens or halogen salts (e.g., bromine, iodine, zinc chloride, and sodium hypochlorite), organic halides or organic acid halides (acetyl chloride and benzyl chloroformate), acid anhydrides, and some organic materials (e.g., phenol or carbolic acid). In the case of metals, corrosion is determined by the extent of oxidation of metals reacting with water or oxygen. For example, iron can be weakened by the oxidation of iron atoms, a phenomenon well known as electrochemical corrosion [20], or more commonly known as "iron rust." Many structural alloys corrode merely from exposure to moisture in the air.

Most ceramic materials are almost entirely immune to corrosion due to the strong ionic and/or covalent bonds that hold them together, which leave very little free chemical energy in the structure [21]. However, in some ceramics, corrosion can be realized by the dissolution of material reflected by obvious discoloration. In other words, unlike metals, when corrosion occurs in ceramics, it is almost always a simple dissolution of the material or chemical reaction, rather than an electrochemical process.

In polymers and fibers, corrosion and degradation may result from a wide array of complex physiochemical processes that are often poorly understood. The complexity of these processes stems from the realization that due to the large molecular weight of polymers, very little entropy can be gained by mixing a given polymer mass with another substance, making them generally difficult to dissolve. In general, polymer corrosion or degradation can be observed in various forms including [1, 2, 22] swelling or volume change and reduction in polymer chain length by ionizing radiation (e.g., ultraviolet light), free radicals, oxidizers (oxygen, ozone), and chlorine. Treatments such as UV-absorbing pigment (e.g., titanium dioxide or carbon black) can slow polymer degradation. One example of fibers known for its easy degradation is rubber or spandex. This type of filaments being elastomeric can degrade by exposure to many chemicals or ultraviolet light. One way to avoid this degradation is to use this filament as a core in a yarn wrapped by another fiber for protection.

In general, corrosion or material degradation is a difficult parameter to evaluate due to the nonstandard way of reporting its values for various materials. In addition, the environment causing corrosion is not always known. Indeed, corrosion or degradation can also be caused or promoted by microorganisms that attack

both metals and nonmetallic materials. This is generally known as microbial corrosion or bacterial degradation [23].

7.5 Material cost

The 21st century came with many volatile and unstable global markets in both energy and material costs. In addition, restrictions on using higher energy and natural resources have been increased as a result of the increasing trend toward sustainable development. These are not temporary changes, and they are likely to continue throughout this century. Therefore, more creative approaches must be implemented to optimize the use of material and minimize energy consumption. In Chapter 6, these points were made clear in the context of the conversion from the traditional linear economy to circular economy in which one industry's waste becomes another's raw material. Now, corporations, scientists, and engineers have come to realize that the future will not be one of unlimited access to water and energy, abundant raw materials (agricultural and petroleum-based), unregulated emissions, or material waste. Perhaps, some statistics can illustrate the substantial increase in the cost of raw materials in recent years. According to the world Bank [24], nonfood agricultural material prices have increased by 117% since 2000. The price of rubber has been increased by 359% since 2000. In 2013, cotton's price was spiked by over 100%. The nominal price of steel was increased by up 167% since the turn of the century, which influenced a range of industries such as construction, automotive, and transport. As a result, some companies have begun to pioneer new design models that enable them to retain ownership of the materials used in the products they sell.

In many design applications, the cost of material is considered as the most critical criterion in determining which material to select. Different material types will have different costs depending on a number of factors including [25–27] (a) supply and demand rules; (b) property uniqueness; (c) availability determined by the costs of extracting, fabricating, or modifying material structure; (d) technology cost determined by machining, forming, and heat treatments; (e) ease of material handling determined by the cost of assembly, number of components to be manufactured, storage, retrieval, packaging, and transporting; (f) the energy required to process or handle the material; (g) reliability; and (h) material by-products (derivatives, waste, etc.). These factors result in distinct cost differences between different categories of materials. For example, materials such as composites, ceramics, and metals could have comparable market prices, particularly if they are competing for the same market. On the other hand, polymers and rubbers are generally less expensive than these three categories of material, followed by wood and porous ceramics. Within the same category of material, one can find substantial price difference as a result of the cost of modifying a material to meet certain performance characteristics. For example, a galvanized steel sheet is expected to be more expensive than billets, blooms, or steel slabs. In addition, high-modulus pitch-based carbon fibers are substantially more expensive than low-modulus, nongraphitized mesophase pitch-based fibers.

Another important cost factor that can greatly assist in the decision-making process of material selection is the relative cost contribution of material with respect to the total cost of manufacturing a product [27]. This relative cost can range from approximately 20% to 90% depending on the type of material and the product in question. For example, products such as expensive jewelry and dental alloy in which precious metals are used (e.g., gold, platinum, and palladium) can be associated with material cost of up to 85% or 90% of the cost of the final product. Similarly, some electronic products use metals that are sold as bonding wires, evaporation wire and slugs, and sputtering targets for the deposition of thin films. This often results in setting prices largely in accordance to the metal price with minor fabrication charge. The other extreme can be found in products such as precision nongold watches in which the cost of metals provides a minor contribution to the final product cost, which is mainly fabrication. For fibrous products, one can also find a wide range of relative cost contributions of material, which typically fall between the two extremes mentioned earlier. For example, the cost of cotton fiber typically contributes by a range from 50% to 70% to the total final cost of spun yarn. For some technical or function-focus fibrous products, the contribution of raw material cost can vary widely depending on the type of fibers used and the weight or volume fraction of fibers in the product composition.

In view of the earlier points, the key aspect in evaluating material cost is how this cost is translated into a product value reflected in an optimum product performance and whether this value is ultimately appreciated by the user of the product. The interrelationships between cost, value, and performance can be visualized using a simple triangle as shown in Fig. 7.7. A cost-value-performance triangle [25] is determined by three basic dimensions, each of which is scaled from 0% to 100%. These may be considered as ordinal values used to rank materials according to the three criteria

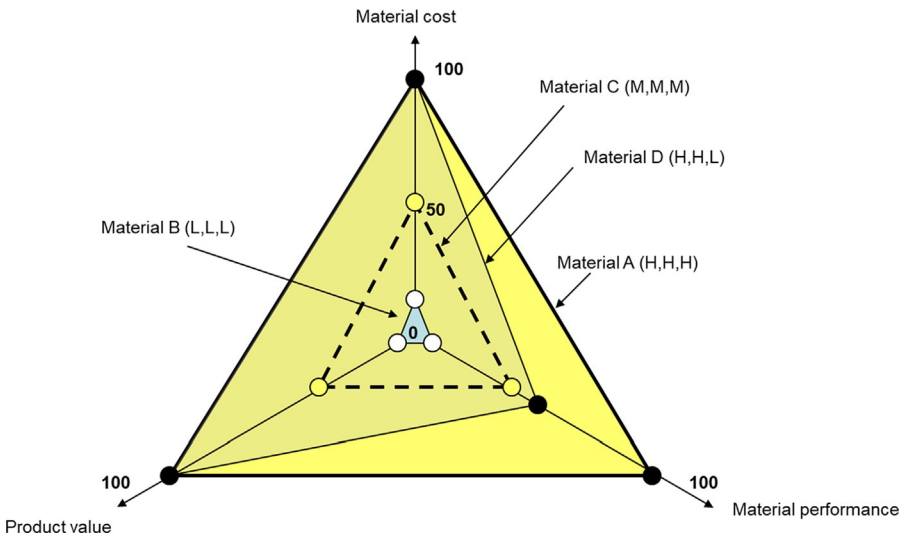


Fig. 7.7 Material cost-value-performance triangle [18].

of the triangle or as interval values used to rank materials in such a way that numerically equal distances on the scale represent equal distances in the criterion being measured. The scales of the three dimensions of the cost–value–performance triangle are determined by two extreme scenarios of interrelationships:

1. High cost-high performance-high value (e.g., material A). In this case, the high cost of material is directly translated into high value of the product in the marketplace reflected in superior product performance. In other words, a linear relationship exists between value, performance, and cost. Most liability-oriented products (e.g., aircrafts, jet engines, construction products, tires, and airbags) will contain materials of this category.
2. Low cost-low value-poor performance (e.g., material B). This category of material hardly exists in the marketplace.

Between these two scenarios, one can find many materials of wide ranges of cost, value, and performance (e.g., materials C and D). The cost-value relationship is often determined by a complex combination of market factors that must be considered collectively to establish a reliable relationship [25]. Cost-performance relationships on the other hand can be established during the design process and particularly in the material selection phase. This aspect is discussed later.

7.5.1 Cost-performance relationship

In many industries, raw material cost is typically a direct function of material performance, with high-price materials performing better during processing and in relation to end-product functional characteristics than low-price materials. In other words, the cost of raw material is a direct function of performance. In these industries, the value of raw materials is directly reflected in the value of end products in the marketplace. In many applications in the traditional textile industry, attention to the relationship between the cost and the performance of raw material has been peripheral and secondary at best. For example, cotton fibers being a commodity exhibit a market price that largely reflects the global supply and demand with only partial attention to performance. Within a given cotton type or source, the price of cotton fiber is heavily determined by the percent of trash and foreign matter content, which are inevitable consequences of cotton harvesting. Key fiber attributes such as fiber length, fineness, and strength are weighed significantly less than trash content in determining the market value. As a result, the focus in cotton fiber production has been on intensely cleaning cotton to remove trash particles with the consequences being overstressing fibers, creating short fiber content and significant amount of knotted fibers or neps. This practice creates a gap between the cotton market value and the technological or performance value of cotton fibers [6].

Cost is certainly a function of price, but using low-price raw material or blending expensive raw material with cheaper raw materials does not guarantee an overall reduction in manufacturing cost. Blending fibers has been a common practice in the textile industry for hundreds of years for the sole objective of reducing total manufacturing cost. However, it has been primarily a manufacturing practice and not a design aspect. Unfortunately, blending fibers does not always yield a linear

additive average of fiber properties. For example, blending high strength fiber with low strength fibers even of the same fiber category such as cotton fibers may result in a yarn strength that is lower than the anticipated values of yarn strength produced from either fiber separately. This is because of the complex nonlinear phenomenon associated with yarn strength, which is highly sensitive to the breaking elongation of each fiber type [6, 9]. When cotton fibers are blended with synthetic fibers, nonlinearity becomes even greater by virtue of the differences in fiber bulk density and the large difference in the mechanical properties of the two fibers. Yet, this practice is often based on the price of cotton and polyester in the marketplace.

The point of the earlier discussion is that selection of raw material should be based on the values of inherent properties that can satisfy the desired functional performance of products at an optimum manufacturing cost. This means that a cotton or polyester fiber that is suitable for a certain yarn (say, coarse carded yarn) may not be suitable for another yarn (say, fine combed yarn). This requires a development of cost-performance relationships that primarily a product design aspect and cannot be left to manufacturing trial and error practices.

7.5.2 Cost-performance equivalence

Cost-performance analysis can be performed using well-developed relationships between cost and some performance characteristics that allow a fair comparison between different material types. In the design of fiber composites and technical textiles, one of the key parameters determining the cost of material is material weight or density. As a result, cost-property comparison between two materials should be based on weight or structural equivalence. This is particularly important when two materials of different strength or stiffness are compared. In this case, the relative weight of each material for equal strength or stiffness should be determined. To illustrate this point, suppose a fiber of cross-sectional area, A, will be subjected to an axial tension, F. This will result in the following equation of working stress:

$$\sigma_w = \frac{\sigma_{yield}}{factor\ of\ safety} = \frac{F}{A}$$

When two fiber types M and N are compared under the same load, the condition of equal load-carrying ability in both fibers is given by

$$A_M \sigma_{wM} = A_N \sigma_{wN}$$

$$\frac{\pi {d_M}^2}{4} \sigma_{wM} = \frac{\pi {d_N}^2}{4} \sigma_{wN}$$

$$or\ \frac{d_N}{d_M} = \left(\frac{\sigma_{wM}}{\sigma_{wN}}\right)^{1/2}$$

where d_M and d_N are the diameters of fiber M and fiber N, respectively.

The fiber weight is

$$W = \rho V = \rho AL = \rho \frac{\pi d^2}{4} L$$

where ρ is the fiber density, V is the volume, and L is fiber length.

Thus,

$$\frac{W_M}{W_N} = \frac{\rho_M {d_M}^2 L_M}{\rho_N {d_N}^2 L_N} = \frac{\rho_M \sigma_{wN} L_M}{\rho_N \sigma_{wM} L_N}$$

For a constant length,

$$\frac{W_M}{W_N} = \frac{\rho_M {d_M}^2}{\rho_N {d_N}^2} = \frac{\rho_M \sigma_{wN}}{\rho_N \sigma_{wM}}$$

The earlier equation yields the weight ratio as a function of fiber density ratio and working-stress ratio. It indicates that the weight per unit strength is $W_s = \rho/\sigma$. It also allows for the inclusion of cost comparison provided that the cost per unit weight of each material (c_M and c_N) is known. For weights of fibers M and N of W_M and W_N, the total costs of fibers M and N are $C_M = c_M \cdot W_M \,\&\, C_N = c_N \cdot W_N$. Accordingly,

$$\frac{C_M}{C_N} = \frac{c_M W_M}{c_N W_N} = \frac{c_M \rho_M \sigma_{wN}}{c_N \rho_N \sigma_{wM}}$$

This equation indicates that the cost per unit strength can be generally expressed by the following formula:

$$C_s = \frac{c\rho}{\sigma_w}$$

Similar expressions of cost per unit property can be derived for different cross sections and loading conditions [7]. The significance of the earlier equivalency analysis stems from the fact that it provides an objective comparison between different material types in relation to weight requirements and associated costs. To illustrate this point, suppose that materials for two fibers of the same length are being compared: steel and Kevlar. If the length of the fiber is fixed and the working stresses of the two fibers are the same, the weight ratio will be

$$\frac{W_K}{W_S} = \frac{\rho_K \sigma_{WS}}{\rho_S \sigma_{WK}} = \frac{\rho_K}{\rho_S} = \frac{1.44}{7.86} = 0.183$$

This means that the weight of Kevlar required to meet this working stress is only a fraction (0.183) of the weight of the steel. If the cost of Kevlar is, say, \$20/lb. and that of steel is \$5/lb., then the cost comparison of these two materials can be expressed by

$$\frac{C_K}{C_S} = \frac{c_K \rho_K \sigma_{wS}}{c_S \rho_S \sigma_{wK}} = \frac{20 \times 1.44}{5 \times 7.86} = 0.733$$

This means that the cost of Kevlar will also be a fraction of the cost of steel despite its higher cost per pound.

7.6 Effects of technology on material selection

Understanding the technology involved in making a product can have a significant effect on the choice of appropriate material for the intended product. In the area of fiber-to-fabric engineering, numerous examples can be listed in which the impact of material on the technology used or the effects of technology on material performance can be demonstrated. To illustrate this point, two examples of textile materials are discussed later.

7.6.1 Spinning and manufacturing of microdenier fibers

Microdenier fibers are synthetic fibers (e.g., polyester, nylon, and acrylic fibers) of very fine diameters; they can be one hundred times finer than human hair, and some are of diameter that is less than half the diameter of the finest silk [28–31]. They are commonly defined as the category of fibers of <1.0 denier. Some synthetic fibers of denier as low as 0.001 were designed by Toray of Japan. Microdenier fiber is the primary choice for many products, traditional and technical textiles. For traditional apparels, they simulate the effects of natural fibers such as silk and cotton fibers at much smaller diameters. The high aspect ratio (length/diameter ratio) of these fibers provides great flexibility and high packing density of fiber strands. These are the important attributes required for key performance criteria such as comfort, fit, porosity, and air or water permeability. For technical textiles, the same characteristics make microdenier fibers an excellent choice for many applications such as filtration, wipe cleaning, thermal applications, and sound insulation.

Unfortunately, the desirable attributes of microdenier fibers also introduce many challenges during fiber production and during manufacturing. The required superfine diameter of this type of fibers makes them very fragile to be produced directly from extrusion units. As a result, most microdenier fibers are generated from bicomponent polymers using precise spinning technologies. Some are made using bicomponent fibers that split apart mechanically (e.g., hydroentangling). Others are made by making bicomponent fibers from which one material is dissolved, leaving the microdenier fiber behind. During manufacturing of microdenier fibers into yarns or fiber webs, other challenges are introduced. The high aspect ratio of these fibers makes them extremely flexible, and this increases the tendency for fibers to curl and entangle during manufacturing, forming a great deal of fiber neps. In addition, the high density of microfiber strands can result in excessive fiber breakage by the mechanical wires of opening and carding units. Accordingly, when microdenier fiber is the material of choice, the manufacturing process must be optimized

through consideration of critical parameters such as the number of stages of processing, the wire area density of the opening units, draft settings, carding speed, and production rates [28, 29].

7.6.2 Sizing of spun yarns

The earlier example demonstrates a unique case in which the same material attributes that yield desirable performance criteria also create processing difficulties. In other situations, materials may be selected despite prior knowledge of anticipated structural deficiency and manufacturing difficulties provided that some external treatments can be applied to overcome these flaws. For example, all staple-fiber yarns cannot be woven as spun due to the poor surface integrity that makes them weak against the high abrasive actions imposed by the weaving process. These yarns generally exhibit low abrasion resistance, and high level of hairiness [6]. These problems are largely caused by the discrete nature of staple fibers and the limited ability of the current spinning systems to consolidate fibers into compacted structures. Since staple-fiber yarns represent an inevitable material choice for numerous traditional fibrous products, they must be woven into fabrics despite their poor surface integrity. This is achieved using a chemical surface treatment called "sizing or slashing" applied to the yarn surface prior to weaving. This treatment reduces yarn hairiness significantly and improves abrasion resistance. Chemicals used in the sizing process (preferably, natural starch) are later removed during fabric finishing in a process called "desizing." This issue represents an excellent opportunity for design engineers to overcome a historical problem by developing fibers that can be spun into yarns of good surface integrity so that the cost of chemical treatment, which can be as high as 80% of the cost of sizing, can be saved.

7.7 Design-direct versus value-impact performance characteristics

The choice of raw material should also be made in view of two key categories of performance characteristics: (a) design-direct performance characteristics and (b) value-impact performance characteristics. The first category implies the choice of raw material that can directly yield the functional performance expected from the product. Typically, many materials may be suitable to meet the desired levels of this category of performance characteristics, and the choice should be based on an optimum combination of material properties and cost-related factors. The second category implies the choice of raw material that can result in a significant added value to the product that can be felt and appreciated by the user of the product to such an extent that the user would not hesitate to pay premium for the product. In this case, the cost of raw material may be relatively high, but the added value can offset this high cost. This point is demonstrated by the example later.

7.7.1 Fiber selection for carpet piles

This example illustrates a common case where the choice of a certain material may seem to be economically inappropriate due to its high market price in comparison with other competing materials, yet consideration of cost-performance relationships may indeed result in revealing other economical advantages that support the appropriateness of the expensive material. The product under consideration is carpet piles, the primary component of commercial carpets. The uniqueness of this product in relation to the subject of this chapter is that it can be made from many different materials, which makes material selection a key aspect. Most carpet tiles commonly use four fiber types: wool, polyester, polypropylene, and nylon fibers. Each one of these material candidates has strengths and weaknesses that should be fully recognized prior to selecting the appropriate fiber for this product.

Following the basic steps of material selection discussed earlier (see Fig. 7.8), suppose that the problem statement associated with this fibrous product is, "what is the most appropriate fibers for developing carpet piles for heavy-traffic carpets that are likely to be subjected to high cyclic loading, potential stain, appearance-retention problems, and possible flame? Based on this statement, it is obvious that material type represents a core issue for this product. Moving forward to material criteria, one will find that all material candidates in this example can be manufactured at high degree of efficiency as each one has been used in this type of product for many years with great experience of the manufacturing procedures and the criteria suitable for each type

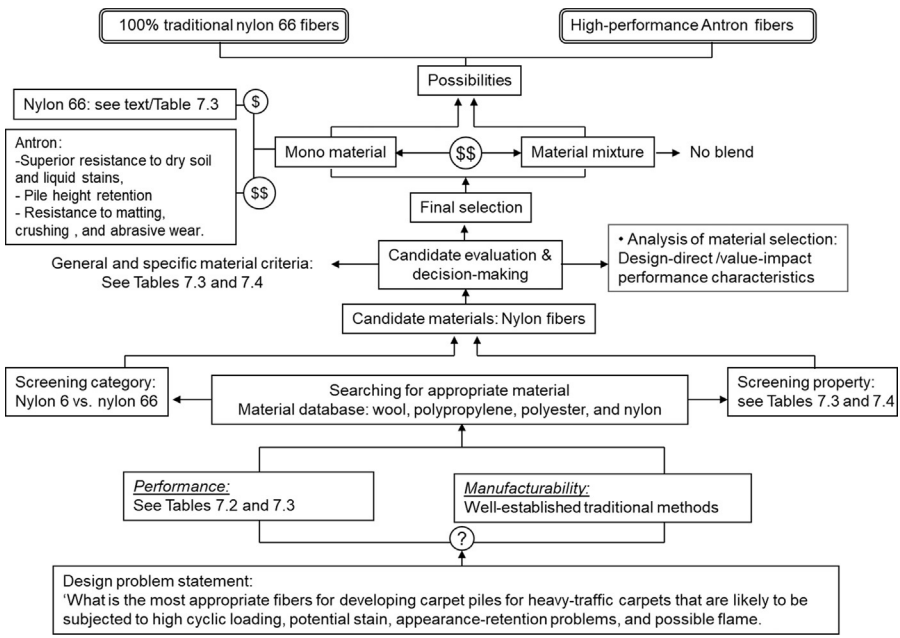


Fig. 7.8 Material selection steps for carpet pile fibers.

[32]. In other words, the conditions under which any of these fiber types is likely to be processed are largely well established. With regard to performance criteria or the service and environmental conditions under which the material in this product is likely to perform, 10 primary performance criteria can be listed for most applications. These are illustrated in Table 7.2. Note that fiber type is a common factor in all criteria.

The challenge of this design problem is that the 10 criteria described in Table 7.2 cannot be met using one type of fiber material. This is evident by the general comparison between the different fiber types shown in Table 7.3. As a result, the design engineer should rank these criteria in the order of their importance with respect to the specific application or the target product. Alternatively, a weight factor can be assigned for each performance criterion depending on its value toward product performance. It is also useful to establish a scaled comparison of different materials to assist in making decision about which materials to consider in the initial selection. Table 7.4 shows a rough scaled comparison on a ranking scale from 0 to 10, with 10 being excellent performance.

Upon establishing and prioritizing the key performance criteria, the next step of material selection will be to screen fiber category and fiber property. This will result in selecting a set of fiber types and fiber characteristics that have potentials for use in this type of product. As indicated earlier, information gathering is a critical task in this basic step. The fiber categories in Tables 7.3 and 7.4 represent one natural fiber (wool) and three synthetic fibers. Wool fibers are traditional carpet fibers that have been used for hundreds of years. They offer deep, rich look, and special feel that are desired by

Table 7.2 Basic performance criteria of carpet pile fibers [32, 33].

Performance criterion	**Contributing factors**
Resiliency	Fiber structure, some enhancement modifications, and pile density
Appearance retention	Fiber structure (cross-sectional shape, and denier) and pile density
Abrasion resistance	Fiber type and the density of face fibers (more tightly packed yarns will result in high wear resistant)
Pilling and fuzzing	Fiber type, yarn structure, and finish treatments
Soil and stain resistance	Fiber type, fiber surface treatment, color, texture, dyes, and fiber structure
Sunlight resistance	Fiber bulk and surface structure and fiber treatments
Static	Fiber structure and treatments
Carpet feel or hand	Fiber type, surface density, and cross-sectional shape
Resistance to mildew	Fiber type and fiber treatments
Flammability	Fiber type, modification, construction methods, dyes, padding and even carpet installation methods

Table 7.3 Descriptive comparison of performance characteristics of different carpet pile fibers [32, 33].

Performance criterion	Wool	Polyester	Polypropylene	Nylon
Resiliency	Excellent	Good to fair	Good (avoid high piles)	Good to excellent
Appearance retention	Excellent	Fair	Fair	Excellent
Abrasion resistance	Good to excellent	Good to excellent	Excellent	Excellent
Pilling and fuzzing	Fair	Fair for staple fibers	Very good	Fair (for staple fibers) Excellent (for filament)
Soil and stain resistance	Good to excellent	Good to excellent (oily stains should be promptly treated)	Good if oily soils and stains are treated promptly	Good to excellent
Sunlight resistance	Poor (degrades under ultraviolet rays)	Good (weaken with prolonged exposure)	Poor (suffers strength loses and deteriorates unless chemically modified)	Good (some special dyes can be used to prevent sun damage)
Static	Builds up at low humidity (can be treated)	Builds up at low humidity (can be treated)	Builds up in low humidity but at a lower level than nylon or polyester	Builds up at low humidity (can be treated)
Carpet feel or hand	Warm, soft	Finer deniers are soft and silky	Waxy, soft	Varies from warm and soft to cold and coarse
Resistance to mildew	Poor if damp or soiled (can be treated)	Excellent	Excellent	Excellent
Flammability	Burns slowly	Burns slowly, melts; some are self-extinguishing. Chemical odor	Melts at low temperatures (170°C); burns and emits heavy, sooty, waxy smoke. Paraffin wax odor. Pulling a heavy object across the carpet surface can cause enough friction to melt the carpet fibers	Burns slowly, melts in direct flame; self-extinguishing. Structure may alter what occurs. Celery-like odor

Table 7.4 Scaled-comparison of performance characteristics of different carpet pile fibers.

Performance criterion	Wool	Polyester	Polypropylene	Nylon
Resiliency	10	5–6	5–6	6–9
Appearance retention	10	4–5	4–5	10
Abrasion resistance	6–9	6–9	9–10	9–10
Pilling and fuzzing	4–5	4–5 (staple) 8–10 (filament)	7–9	4–5 (staple) 8–10 (filament)
Soil and stain resistance	7–9	7–9	5–6	7–9
Sunlight resistance	3	5–6	3–4	5–6
Static	4	4	4	4
Carpet feel or hand	8	6	6	6
Resistance to mildew	5–6	8–10	8–10	8–10
Flammability	4	5	5	5

Excellent = 10, Very Good = 7–9, Good = 5–6, Fair = 4–5, Poor = 0–3.

most residential carpet consumers. However, wool fiber has many limitations, some of which are performance related and others are cost related. Wool is inherently staple fiber, making it sensitive to pilling or fuzzing; it tends to "wear down" or wear away the piles. In some cases, bald spots may occur as a result of heavy traffic loads. Although it has high resilience, the fiber is relatively weaker than the synthetic fiber candidates. It is not easily treatable or modifiable for overcoming soil and stain effects. However, it cleans well with appropriate cleaning methods. Since wool can hold 10 times its weight in moisture, it is susceptible to shrinking and mold and mildew growth. When cost is an issue, the price of wool is relatively high (almost double the price of nylon per yard) making it unreachable by most consumers.

As a result of the earlier performance and cost constraints of wool, its choice may be restricted to some specific applications such as in-door, infrequently used, and luxurious areas. For most commercial carpets, only synthetic fibers are considered. In this regard, category and property screening can become very involved as the competition in this area is strong and developments in all synthetic fibers represent an ongoing effort to gain a larger market share in this highly profitable application.

Assuming that wool is eliminated from the list of potential candidates, the focus should then be shifted to synthetic fibers. Polyester fibers are made from terephthalic acid and ethylene glycol, offered primarily as a staple product for carpets. They are mainly used in residential and a few commercial applications. The fiber has good color clarity, colorfastness, and resistance to water-soluble stains. It is also environmentally suitable as many staple polyester yarns can be produced by recycling plastic bottles. Indeed, some studies by polyester producers suggested that this "food-grade" PET polyester fiber may exhibit better quality than "carpet-grade" polyester fiber [32].

Polypropylene fibers are known as olefin. The fiber-forming substance of olefin is any long-chain synthetic polymer composed of at least 85%, by weight, of ethylene, propylene, or other olefin units. Polypropylene fibers are offered primarily as continuous filaments with some staple product available. They are primarily sold as solution-dyed or predyed fiber. Olefin fibers are famous for their resistance to fading, ability to generate low levels of static electricity, inherent resistance to stains, and good resilience. They are also relatively cheaper than other synthetic fibers.

Nylon fibers were first used for carpet in 1959. Now, they are the most frequently used carpet fibers. It is a fiber-forming substance of any long-chain, synthetic polyamide having recurring amide groups as an integral part of the polymer chain. It can be produced in continuous-filament form or staple-fiber form. Typically, nylon is produced as a solution-dyed fiber or white to-be-dyed yarn. Nylon fibers are highly desirable due to their exceptional durability, versatility, and reasonable pricing. They can be dyed in an endless variety of colors and made into numerous styles and textures for residential and commercial applications.

The general comparison earlier gives the design engineer some ideas about the differences between potential fiber candidates. Obviously, further comparative analysis should be made in which the basic steps of material selection may be repeated to narrow down the choices in view of the specific objectives and the performance criteria required. In this regard, more information about the candidate materials may be needed. For example, nylon fibers are available in two different types: nylon 66 and nylon 6. The former has a tighter molecular structure than the latter due to higher level of hydrogen bonding and maximum alignment between molecular chains. Nylon 6 does not have this level of internal bonding, resulting in a more open structure. In addition, nylon 66 has unsurpassed resilience properties; when subjected to 24 h of compression at 100,000 psi, it demonstrates up to 100% recovery [32]. Accordingly, these two fiber types can be of considerable cost difference depending on performance, brand (producer) name, and other supply and demand conditions. As a result, a nylon 66 carpet can have a substantial price difference of up to 30% over a comparable nylon 6 carpet.

Another type of nylon, which is a derivative of nylon 66, is the so-called Antron, a four-hole hollow filament developed by DuPont [33]. This fiber enjoys superior performance in three key carpet criteria: resistance to dry soil and liquid stains, pile height retention, and resistance to matting, crushing and abrasive wear. Soil resistance can also be enhanced by a treatment called DuraTech soil resistant. Obviously, this fiber is more expensive than other nylon fibers.

The performance characteristics associated with the example earlier belong to the design-direct category mentioned earlier. These characteristics suggest that both conventional nylon 66 and Antron represent good candidates of raw material for carpet piles. The fact that Antron is more expensive than conventional nylon 66 may represent a concern to the design engineer as the high cost must be translated into a true value that can be felt and appreciated by the user of the product. This is where value-impact performance characteristics are necessary to justify the higher cost. These may include longer life-cycle, minimum maintenance, lower cost of energy, easy installation, minimum water use, minimum air and land emission, and easy cleaning.

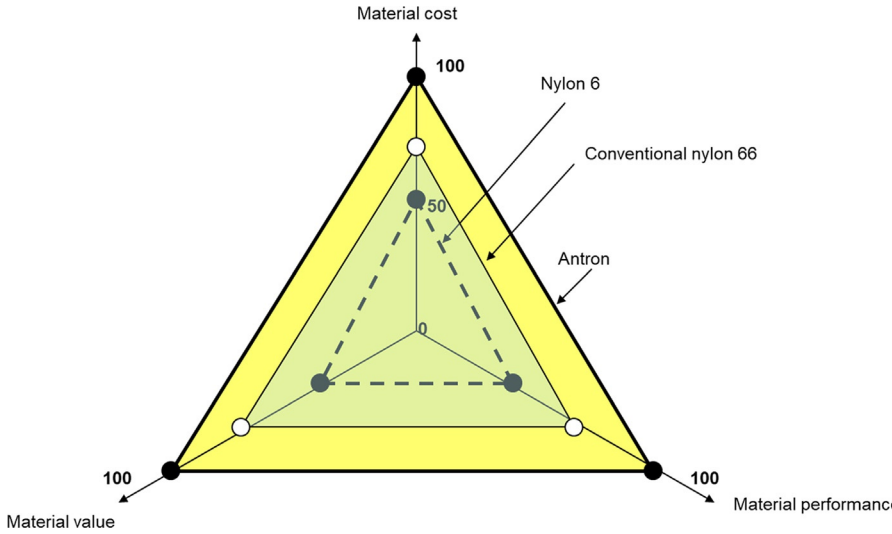


Fig. 7.9 Material cost-value-performance triangle of carpet pile nylon fibers.

According to DuPoint publications [33] based on a case study in which Antron fibers were used in commercial carpets to cover David L. Lawrence Convention Center in Pittsburgh, the use of Antron resulted in the following savings: the equivalence of 18,050 gal of fuel, as much global warming as 56,083 trees absorb in one year, enough air emissions to fill 135 trash cans, enough land emissions to fill 7.9 18-wheeled tractor trailers, and enough water to flush 51,141 toilets. Notice how different these characteristics from the direct design characteristics. With this value-impact information, a better comparison between nylon 6, nylon 66, and Antron fibers can be established using appropriate decision-making analysis that may yield a cost-value-performance triangle as shown in Fig. 7.9.

The earlier example demonstrated how value-impact characteristics can be of critical importance in justifying the use of expensive and high-performance fibers. Later in Chapters 12–15, many examples will be introduced to illustrate the differences between design-direct and value-impact performance characteristics of various fibrous products.

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Fibers

8

8.1 Introduction

In Chapter 7, a textile fiber was categorized as a polymeric material that has a unique linear structure, which is created naturally or man-made. Natural fibers can be of cellulosic sources including cotton, flax, and jute or of protein sources including wool and silk. They can also be of mineral sources including asbestos. Man-made fibers can be subdivided into two categories: regenerated fibers such as rayon, lyocell, cellulose acetate, and triacetate and synthetic fibers such as polyester, polyamide, and polyacrylic. Fibers can also be of inorganic sources including glass and metallic fibers. The availability of many types of fibers provides product designers with a wide range of structural features resulting in many physical and chemical properties that contribute to the performances of numerous end products.

In 2017, fiber production was at a record high of 103 million metric tons [1]. This is an increase of over 900% since 1950 when global fiber production was less than 10 million metric tons. Since the early 2000s, polyester fiber has overtaken cotton fiber and dominated the fiber market. In 2017, the market share of synthetic fibers reached 60%, with polyester fiber alone at 51% of the total global fiber production (more than 53 million metric tons); nylon fiber was about 5.5%, and other synthetic fibers were about 5.5%. Cotton fiber was second in total market share reaching 25% (about 26 million metric tons); wool fiber was about 1 million metric tons or 1% market share; long-vegetable fibers including jute, linen, and hemp were at about 5%; and silk and down had market shares of less than 1%. Cellulosic-based man-made fibers had a market share of 7% (about 6.5 million metric tons). These are the common choices of fiber types in today's product development projects in the textile and garment industry.

The largest use of textile fibers is in the apparel and clothing sector, which was more than 75% in 2017. About 10% of the market share is in household products, and about 12% is in the growing technical textile market. Globally, the value of basic fibrous products (yarns and fabrics) produced by textile mills is estimated to reach the trillion-dollar mark before 2020. The apparel market is also estimated to reach the trillion-dollar mark by the same year leading to an apparel retail market of over $1.6 trillion. On the other hand, the technical textile market is estimated to reach over $220 billion by 2020. The importance of textile fibers can also be realized from the nearly 70 million people working in this industry around the globe.

The expansion of the technical textile market will only mean unlimited potentials for the growth of fiber production worldwide. In this market, fibers are blended or integrated in nonfibrous structures. They are used as temporary binding elements in medical sutures, which must biodegrade instead of being removed and wasted; they are used as carrier for other materials such as electronics in smart fashion; they are incorporated into composite structures in which metals or other polymeric matrixes

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are used; they are used in construction products partnering with cement and other construction materials; they are used in the human body as artificial organs; they are used to reinforce soil and embankments as geotextiles; and they are used as filtration means in different filters handling numerous types of other materials.

In the context of product design, it is important that engineers of all fields understand the differences between textile fibers and other materials. In this chapter, the key differences between fibers and other materials will be discussed. In addition, an overview of different types of fibers will be presented. By no means, the coverage of textile fibers in this book is intended to be comprehensive or inclusive. Readers interested in learning more detail about textile fibers can refer to many published books on the subject [2–6].

8.2 Basic differences between fibers and other materials

Most fibers are essentially polymeric-based materials, and they largely share many of the inherent characteristics of polymers. For example, the Cambridge charts [7] shown in Fig. 7.2 of Chapter 7 indicated that polymeric materials exhibit bulk density ranging from about 900 to 2800 kg/m^3 (0.9–2.8 g/cm^3). As shown in Fig. 8.1, most conventional fibers fall in the range from 0.9 to 1.6 g/cm^3. Some specialty fibers such as carbon and glass fibers have density in the range from 1.75 to 2.6 g/cm^3. The uniqueness of a textile fiber will typically stem from three basic attributes: linearity, flexibility, and light weight. These attributes make fibers easily manipulatable in numerous products and constructions. In the following sections, a review of some of the unique characteristics will be presented. These will include fiber structure, deformation behavior, strength parameters, thermal conductivity, aspect ratio, and surface characteristics.

8.2.1 Fiber structure

The internal structure of a polymeric fiber consists of small molecules or monomers joined together to form a long molecular chain. As shown in Fig. 8.2, this structure can be described by three basic parameters [8, 9]: (1) the degree of polymerization, (2) the degree of order, and (3) the degree of orientation. The length of the molecular chain depends on the number of molecules connected in a chain, which is generally known as the "degree of polymerization." This is typically determined by the ratio between the molecular weight at a certain point of time during polymerization and the molecular weight of one monomeric unit. Molecular chains may be arranged in a dominantly random order, commonly known as amorphous structure, or in a dominantly organized order, commonly known as crystalline structure. Most fibers exhibit structures that are partially crystalline and partially amorphous. This is commonly known as the degree of order, with highly crystalline fibers being of high molecular order. In addition, fibers can be made at different levels of molecular orientation by stretching the molecular chains to different levels of draw ratio; this is known as the degree of orientation.

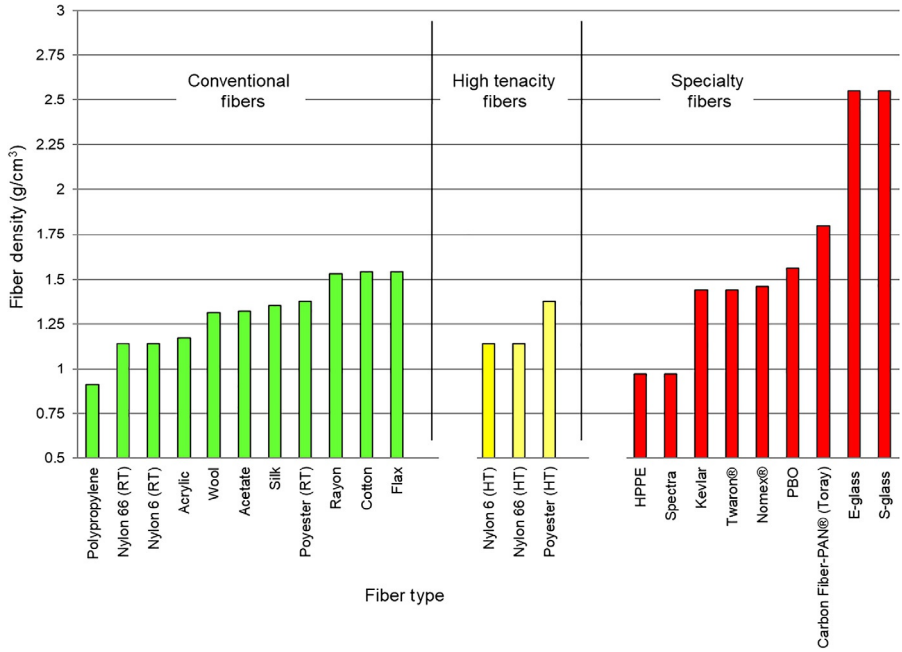


Fig. 8.1 Typical values of density of different fiber types.
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8.2.2 Fiber deformation behavior

To understand the unique strength characteristics of fibers, it is important to provide few comments on the nature of their mechanical behavior in comparison with other materials [10–12]. In general, crystalline metals and ceramics will typically deform by a very small amount (often unnoticeable) at small levels of applied stresses. Typically, small loads will result in small displacement of the metal atoms, less than 10% of their interatomic distances. Fibers being a polymeric material will respond easily to external loading even at very small levels. Within elastic limits, polymer molecules recoil almost immediately from the load, but some polymers may exhibit a slight delay in the elastic recoil [10, 11]. When the applied stress exceeds the elastic limit, polymeric materials undergo the phenomenon of polymer yielding, which is the

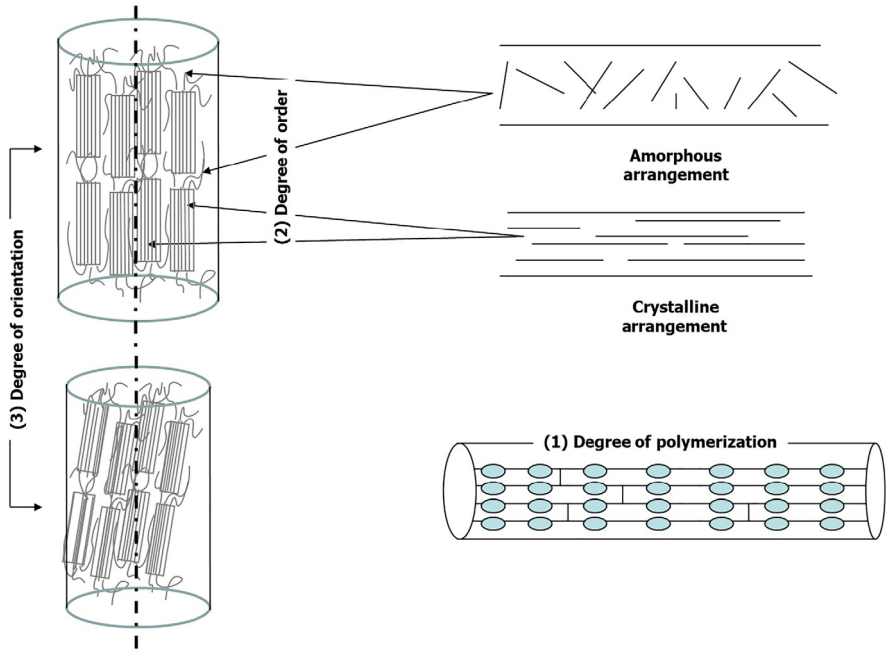


Fig. 8.2 Basic structural features of fibers.

onset of a permanent or irreversible deformation. For noncrystalline (or amorphous) polymeric materials, yielding will result from molecular uncoiling, leading to a neck forming at the yield point, which is followed by an overall drop in stress. At the neck region, the folded chains become aligned. The microscopic thinning down in cross section results in a local increase in the stress, and any deformation occurs preferentially there. This helps the neck propagate crosswise under a steady load, in a process known as cold drawing. Any deformation produced beyond the yield point is not recoverable. In a crystalline polymer, the unfolding of chains begins in the amorphous regions between the lamellae of the crystals. This is followed by breaking up and alignment of crystals.

When time is a factor in rationalizing the mechanical behavior, one will find that metals and ceramics behave differently from fibrous materials. Typically, crystalline metals and ceramics deform plastically by dislocation motion, which is in step time wise with the applied stress. Fibers, after passing the elastic region, also deform plastically under stress by sliding of long-chain molecules past one another via the breaking of the weak secondary intermolecular bonds. The difference is that plastic deformation can increase with time without an increase in stress. Another difference is that the deformation is not purely plastic particularly at the initial stage; it is a mix of plastic and elastic deformation. With further time, deformation can be purely plastic. This overall deformational behavior of fibers is uniquely described as a viscoelastic behavior, implying a combined behavior of fluid and solid [8, 12].

Theoretically, the viscoelastic behavior of fibers and polymeric materials has been simulated by conceptual models such as the so-called Maxwell and Voigt models, which consist of a series of springs and dashpots [8, 12]. In this regard, two common time-dependent phenomena should be realized: creep and stress relaxation. In simple terms, creep occurs when a constant force is continuously applied on a component, causing it to deform gradually with time. As a result, it is a strain-time relationship with an increasing strain over time. The extent of creep will largely depend on the constant force applied. For thermoplastic polymers, creep will also depend on the temperature with the increase in temperature leading to faster deformation. A classical model of the creep behavior of a material has three stages of strain versus time. The first stage consists of the initial elastic and plastic effects of loading and an initially high but rapidly decaying creep rate. This is followed by steady-state creep in stage two where the rate is linear with time and concludes with tertiary creep where the creep rate rapidly accelerates and ends in failure. Stress relaxation is almost exclusively a characteristic of polymeric materials under constant strain over time. It is typically manifested by a reduction in the force (stress) required to maintain a constant deformation. In classic polymer relaxation theory, the time-dependent behavior is governed by highly developed equations often based on Maxwell or Voigt models and governed by a spectrum of relaxation times for the material.

The effect of temperature on the deformational behavior of fibers is also well documented [4, 8, 13, 14]. Fibers may be subject to high temperatures during processing and during chemical or thermal finishing. A polymeric fiber that melts, softens, or deteriorates under detergent treatments or hot water would make an unacceptable fabric. Fibers made from thermoplastic polymers can be manipulated during processing by raising their temperature above the softening or glass transition temperature (T_g), texturizing or deforming them, and cooling them again below the T_g to set the intended textured structure. Nonthermoplastic fibers can be treated using chemical cross-linking to reduce the loss of energy of deformation and provide better dimensional stability and shape recovery after deformation. For cotton fibers, this type of treatment is commonly known as permanent-press finish, and it functions by forming cross-links between adjacent cellulose polymer chains. These give cotton some elastic and resiliency properties.

8.2.3 Fiber strength parameters

Although most fibers belong to the category of polymer material, their molecular structure and deformational behavior provide them with unique values of strength parameters. In this regard, it will be useful to divide fibers into two main categories: conventional fibers and specialty fibers. The first category represents fibers that are commonly used for traditional fibrous products. These include natural fibers and common synthetic fibers (e.g., nylon, polyester, polypropylene, and acrylic fibers). The second category represents fibers that are commonly used for technical fibrous products (e.g., aramid fibers, carbon fibers, and glass fibers). Values of strength-related parameters of conventional fibers are listed in Tables 8.1–8.3, and those of specialty fibers are listed in Table 8.4. The units used in these tables are those used commonly

Table 8.1 Values of some strength parameters of natural fibers [3, 6, 7].

Fiber type	Tenacity (g_f/denier)		Breaking elongation (%)	Flexural rigidity (g_f/denier)	Elastic recovery (%) at 1%	Elastic recovery (%) at 3%
	Dry	Wet				
Cotton	2.7–4.0	3.5–5.5	4–6	60–70	50	35
Wool	1.8–2.0	1.3–1.4	25–45	4–6	60	
Flax	6–7	7–9	1.5–3.5	160–180	80	65
Silk	4–5	3–4	20–25	50–120	45	40

among fiber and polymer engineers. Values in these tables are also demonstrated in Figs. 8.3–8.5. Examination of these values reveals the following important points:

- As shown in Fig. 8.3, tenacity values of conventional fibers range from about 140 to 850 MPa (0.1 N/tex to about 0.65 N/tex). Some high-tenacity fibers can reach up to about 1200 MPa (0.9 N/tex). Note that synthetic fibers such as nylon and polyester can be produced in a wide range of tenacity depending on the intended applications.
- As shown in Fig. 8.4, some specialty fibers exhibit very high-tenacity values that easily fit within the range of metals and ceramic materials. The level of tenacity of this category of fiber will depend on the emphasis of application. For example, Nomex fiber being essentially a flame-retardant meta-aramid has a tenacity of 0.7 GPa. Kevlar fiber being a strength-oriented product can have a tenacity of about 3 GPa.
- As shown in Fig. 8.5, most conventional fibers, except cotton and flax, have high breaking elongation values (exceeding 15%). Specialty fibers, on the other hand, exhibit low breaking elongation.
- As indicated earlier, the most unique characteristic of fibers is flexibility. This is the characteristic that yields the comfort and fit of traditional fibrous products and the easy assembly and shape manipulation of technical fibrous products. The most common measure of flexibility is the initial modulus, known as Young's modulus. Fig. 8.6 shows another one of Cambridge material charts [7] in which values of Young's modulus for polymers range from about 0.08 to 10 GPa. These values are clearly below those of metals, ceramics, and composite materials. Most conventional fibers exhibit values within this range as shown in Fig. 8.7. Only flax fibers can exceed this range.
- Specialty fibers exhibit Young's modulus values approaching those of metals and ceramic materials. This is clearly illustrated in Fig. 8.8.

8.2.4 Fiber thermal conductivity

Another parameter that distinguishes fibers from many other materials is thermal conductivity. This is the ability of material to conduct heat. The general expression of thermal conductivity is as follows [8–12]:

$$k = \frac{\Delta Q}{A \times \Delta t} \times \frac{x}{\Delta T}$$

Table 8.2 Values of tenacity and elongation of man-made fibers in dry and wet conditions [2–6, 8, 9, 13, 14].

Fiber type	Tenacity (g_f/denier)				Breaking elongation (%)			
	Dry		Wet		Dry		Wet	
	RT	HT	RT	HT	RT	HT	RT	HT
Polyester (filament)	2.8–5.6	6.8–9.2	2.8–5.6	6.8–9.2	24–42	10–25	24–42	10–25
Polyester (staple)	2.4–7.0	5.7–6.9	2.4–7.0	5.7–6.9	12–55	20–34	12–55	20–34
Polyester (partially oriented)	2.0–3.0		2.0–3.0		120–170		120–170	
Nylon 6 (filament)	4.0–7.2	6.5–9.0	3.7–6.2	5.8–8.2	17–45	16–24	20–47	19–33
Nylon 6 (staple)	3.5–7.2				30–90		42–100	
Nylon 6,6 (filament)	2.3–6.0	5.9–9.8	2.0–5.5	5.1–8.0	25–65	15–28	30–70	18–32
Nylon 6,6 (staple)	2.9–7.2		2.5–6.1		16–75		18–78	
Lyocell (Tencel)		4.8–5.0		3.8–4.2		14–16		16–18
Rayon (Fibro) (filament and staple)	2.3	3.0	1.1	1.5	18–22		18–22	
Acetate (filament and staple)	1.2–1.4		0.8–1.0		25–45		35–50	
Acrylic (Acrilan) (staple)	2.2–2.3		1.8–2.4		40–55		40–60	
Olefin (Spectra)		30–35		30–35		2.7–3.6		2.7–3.6
Olefin-polypropylene (filament)	2.5–5.5		2.5–5.5		30–100		30–100	
Olefin-polypropylene (staple)	2.5–5.5		2.5–5.5		30–150		30–150	
Spandex (Lycra)	0.8–1.0				400–800			

Table 8.3 Values of stiffness, toughness, and elastic recovery of man-made fibers [2–6, 8, 9, 13, 14].

Fiber type	Stiffness (g_f/denier)		Toughness (g_f cm)		Elastic recovery (%)		Specific gravity	
	RT	HT	RT	HT	RT	HT	RT	HT
Polyester (filament)	10–30	30	0.4–1.1	0.5–0.7	76/3	88/3	1.38	1.39
Polyester (staple)	12–17		0.2–1.1		81/3		1.38	
Polyester (partially oriented)			1.3–1.8				1.34	
Nylon 6 (filament)	18–23	29–48	0.67–0.90	0.75–0.84	98–100/1–10	99–100/1–8	1.14	
Nylon 6 (staple)	17–20		0.64–0.78		100/2		1.14	
Nylon 6,6 (filament)	5–24	21–58	0.8–1.25	0.8–1.28	88/3	89/3	1.14	1.14
Nylon 6,6 (staple)	10–45		0.58–1.37		82/3		1.14	
Lyocell (Tencel)		30		0.34				1.56
Rayon (Fibro) (filament and staple)							1.53	
Acetate (filament and staple)	3.5–5.5		0.17–0.30		48–65/4		1.32	
Acrylic (Acrilan)(staple)	5–7		0.4–0.5		99/2		1.17	
					89/5			
Olefin-polypropylene (filament)	12–25		0.75–3.0		95/5			
					85/10			
Olefin-polypropylene (staple)					93/5		0.91	
					85/10			
Spandex (Lycra)					97/50 to 99/200		1.2	

Table 8.4 Values of strength parameters of some specialty fibers [3, 15].

Fiber type	Specific gravity (g/cc)	Tenacity (N/tex)	Initial modulus (N/tex)	Breaking elongation (%)
Kevlar29	1.44	2.030	49	3.6
Kevlar49	1.44	2.080	78	2.4
Kevlar149	1.44	1.680	115	1.3
Twaron	1.44	2.100	60	3.6
Nomex	1.46	0.485	7.5	35
HPPE(Dyneema SK60)-1 dpf	0.97	2.800	91	3.5
HPPE(Dyneema SK65)-1 dpf	0.97	3.100	97	3.6
HPPE(Dyneema SK71)-1 dpf	0.97	3.500	122	3.7
Spectra 900-10 dpf	0.97	2.600	75	3.6
Spectra 2000-3.5 dpf	0.97	3.400	120	2.9
PBO poly(*p*-phenylene benzobisoxazole)	1.56	2.54	177	
Carbon Fiber-PAN (Toray)	1.80	2.0–6.0	180–450	0.7–2.0
E-glass	2.55	1.5–2.5	54	1.8–3.2
S-glass	2.50	2.0–3.0	62	4.0
Steel wire	7.85	0.18	26	1.5

where $\frac{\Delta Q}{\Delta t}$ is the rate of heat flow, A is the total surface area of conducting surface, ΔT is temperature difference, and x is the thickness of conducting surface separating two temperature levels.

The earlier expression indicates that thermal conductivity is a direct function of the quantity of heat, ΔQ, transmitted during time Δt through a thickness x, in a direction normal to a surface of area A, due to a temperature difference ΔT, under steady-state conditions and when the heat transfer is dependent only on the temperature gradient. In SI units, thermal conductivity is therefore expressed in W/(m K).

Fig. 8.9 shows typical values of thermal conductivity of some conventional and specialty fibers. Fig. 8.10 shows thermal conductivity values for other common materials. Values in both figures should be taken only for general comparative purposes. Fig. 8.11 shows values of thermal conductivity of highly conductive materials. In general, most fibers exhibit low thermal conductivity, which makes them useful in many heat insulation applications. Specialty fibers such as carbon and glass fibers can have exceptionally high thermal conductivity.

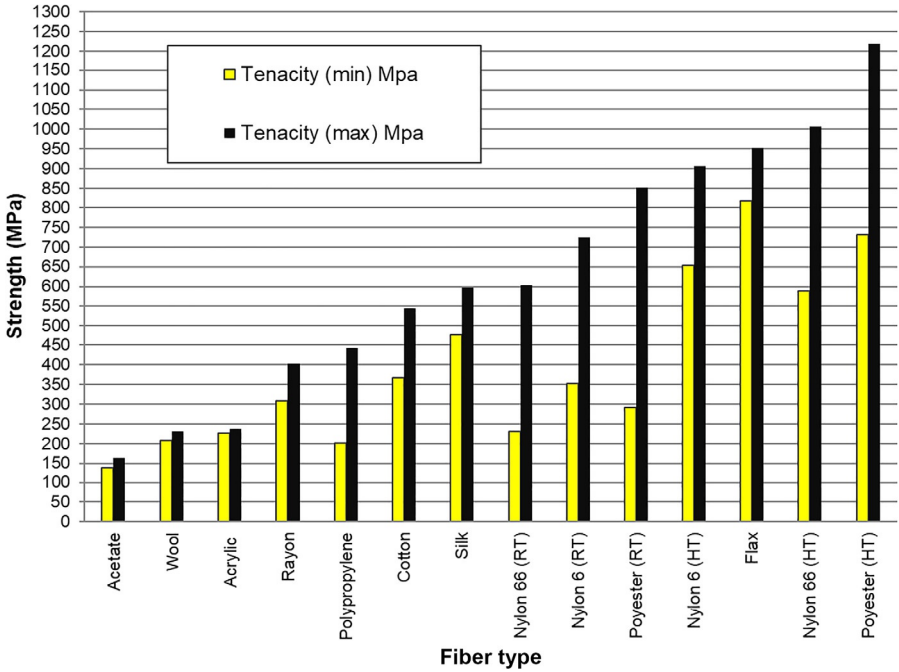


Fig. 8.3 Typical values of strength of different conventional fiber types (*RT*, regular tenacity; *HT*, high tenacity).
Graph developed from data J. Gordon Cook, Handbook of Textile Fibers: Vol. II: Man-Made Fibers, Woodhead Publishing Limited, Cambridge, 2009 (Reprinted 1993, 2001, 2002); J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; J.W.S. Hearle, R.H. Peters, Fiber Structure, The Textile Institute, Butterworths, 1963; B. Lomas, J.W.S. Hearle, W.D. Cooke, Atlas of Fiber Fracture and Damage to Textiles, The Textile Institute, Woodhead Publishing Limited Cambridge, England, 1998; R.R. Franck, Bast and Other Plant Fibers, The Textile Institute, Woodhead Publishing Limited, England, 2005; W.S. Morton, J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962; Y. Elmogahzy, Engineering textiles, in: Integrating the Design and Manufacture of Textile Products, first ed., Woodhead Publishing (Elsevier), UK, 2009; I. Block, Manufactured Fiber, AccessScience@McGraw-Hill, 2002, doi:10.1036/1097-8542.404050, http://www.accessscience.com, last modified: May 6; W. Klein, Man-Made Fibers and Their Processing, The Textile Institute, Manchester, 1994.

8.2.5 Fiber aspect ratio

A key characteristic that makes fibers uniquely distinguished from other materials is the high aspect ratio (length/diameter ratio). Typical values of aspect ratio for fibers may range from 200 to several thousands. From a design viewpoint, fibers of high aspect ratio should result in stronger yarns than those of low aspect ratio by virtue of the long interfiber contact and the possibility of placing more fibers in the yarn cross section [16]. More importantly, high aspect ratio can result in a significant

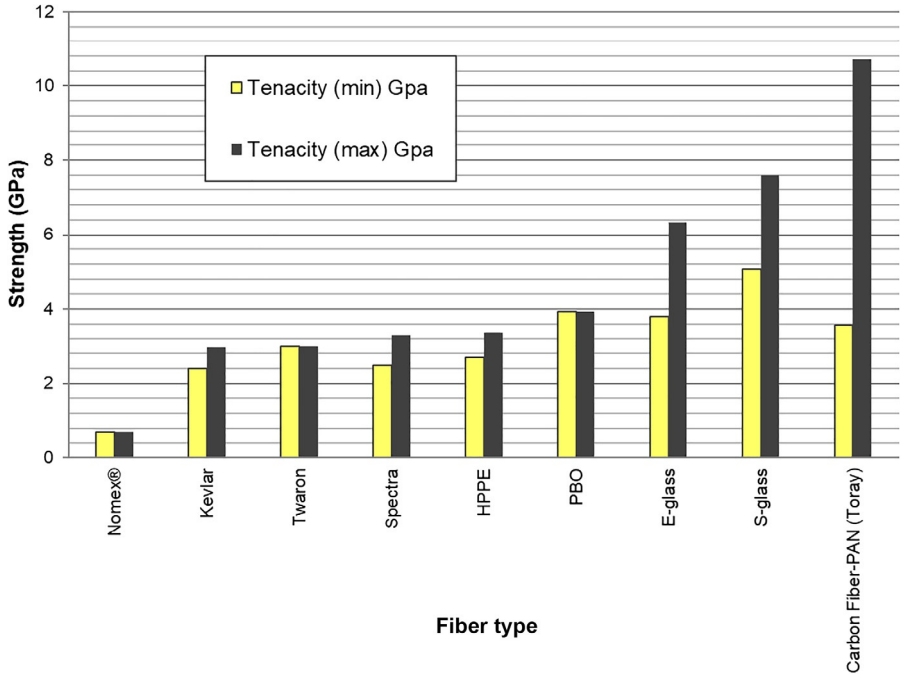


Fig. 8.4 Typical values of strength of different specialty fibers.
Graph developed from data J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; T. Hongu, G.O. Phillips, New Fibers, second ed., Woodhead Publishing Limited, 1997.

improvement in fiber flexibility by virtue of the fact that the bending rigidity of fiber is proportional to the fourth power of dimeter (d^4), where d is the fiber diameter.

As discussed in Chapter 7, entertaining material options should be made in view of the design problem statement and both the performance and the manufacturing criteria associated with the material. When flexibility is the main performance criteria, a design engineer can have multiple options to produce high flexibility as shown in Fig. 8.12. At the fiber level, high flexibility in fibers should result in high flexibility in end products provided that the methods to bind the fibers together into a yarn or fabric can preserve this flexibility or at least minimize its inevitable reduction. In this regard, the material choices will be an inherently flexible fiber, natural staple fibers of high aspect ratios or continuous filaments cut to various lengths, each associated with different aspect ratio. At the yarn level, fiber flexibility can be transferred into yarn flexibility using appropriate spinning method or low twist levels in the yarn. Similarly, fabrics of open constructions using flexible yarns can produce flexible end products [16]. When manufacturing criteria are considered, fiber flexibility has to be of optimum values to avoid manufacturing problems as explained in Chapter 7 using the example of microdenier fibers.

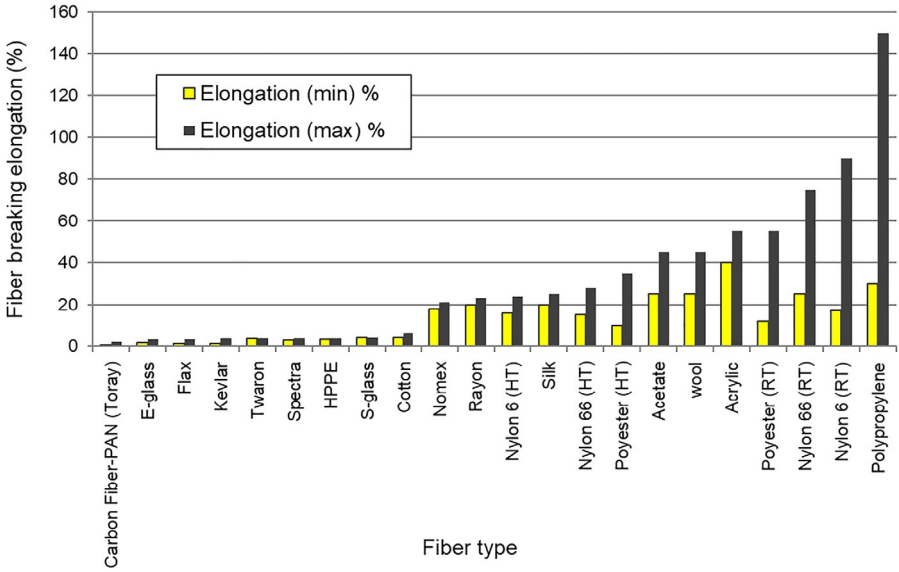


Fig. 8.5 Typical values of elongation of different fiber types.
Graph developed from data J. Gordon Cook, Handbook of Textile Fibers: Vol. II: Man-Made Fibers, Woodhead Publishing Limited, Cambridge, 2009 (Reprinted 1993, 2001, 2002); J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; J.W.S. Hearle, R.H. Peters, Fiber Structure, The Textile Institute, Butterworths, 1963; B. Lomas, J.W.S. Hearle, W.D. Cooke, Atlas of Fiber Fracture and Damage to Textiles, The Textile Institute, Woodhead Publishing Limited Cambridge, England, 1998; R.R. Franck, Bast and Other Plant Fibers, The Textile Institute, Woodhead Publishing Limited, England, 2005; W.S. Morton, J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962; Y. Elmogahzy, Engineering textiles, in: Integrating the Design and Manufacture of Textile Products, first ed., Woodhead Publishing (Elsevier), UK, 2009; I. Block, Manufactured Fiber, AccessScience@McGraw-Hill, 2002, doi:10.1036/1097-8542.404050, http://www.accessscience.com, last modified: May 6; W. Klein, Man-Made Fibers and Their Processing, The Textile Institute, Manchester, 1994; T. Hongu, G.O. Phillips, New Fibers, second ed., Woodhead Publishing Limited, 1997.

8.2.6 Fiber surface characteristics

Different material categories are expected to have different surface structures by virtue of their atomic structure. For example, metals being largely crystalline structures are characterized by surfaces in which atoms are arranged in a largely regular manner [17]. Ceramics being essentially a combination of one or more metals and nonmetallic substance chemically bonded together are expected to exhibit different surface textures [18]. For composite products, surface characteristics of both the matrix and the reinforcing components represent a key structural aspect as it determines both the integrity and the protection of these products. In recent years, a great deal of development of surface physics has been witnessed as a result of the development

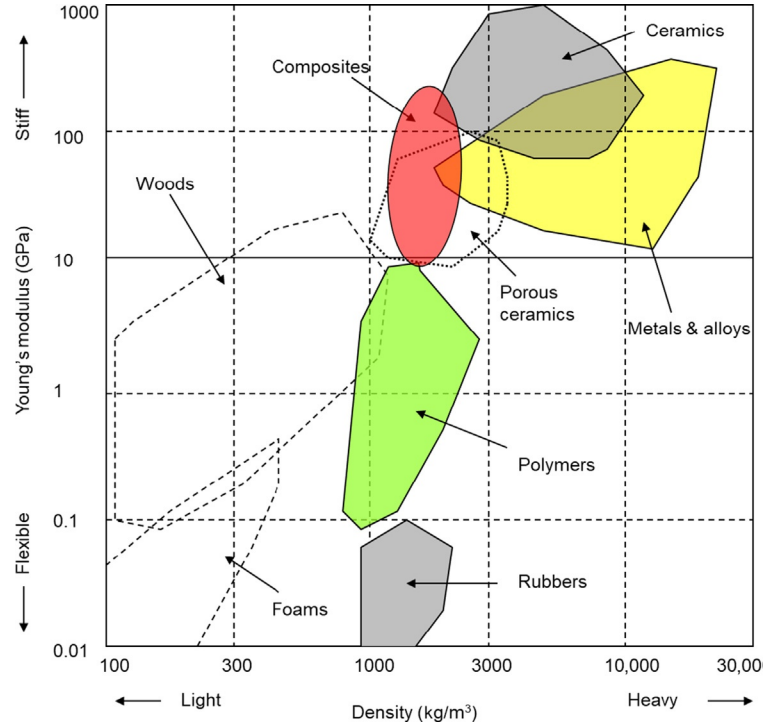


Fig. 8.6 Young's modulus density of different materials [7].

of vacuum technology, new surface sensitive probes, atomic microscopes, and powerful analytical methods [17, 18].

The surface morphology of fibers represents a key design aspect in many product development applications. Different natural fibers exhibit different inherent surface morphologies. For example, cotton fiber has a twisted-ribbon shape along the length of the fiber and a kidney-shaped cross section [19]. Wool fibers on the other hand exhibit a scaly surface, similar to that of human hair, leading to directional frictional effects [20]. Synthetic fibers stem their surface characteristics from various sources including [21] (a) the polymeric surface structure, (b) molecular orientation, (c) fiber cross-sectional shape, (d) fiber crimp, and (e) surface finish treatments. This provides a wide range of key characteristics such as surface cohesion, surface morphology, roughness, moisture management, and cleanability. In addition, the processing performance of most fibers is influenced by surface friction and fiber cohesion. During processing, fibers are subject to repeated rubbing between each other and against machine parts (wires, rollers, etc.). As a result, an optimum cohesion level should be determined for each fiber type [16]. In this regard, high enough cohesion may be required to maintain the bulk integrity of the fiber strand. Meanwhile, too low fiber cohesion may not be desirable as it can result in an

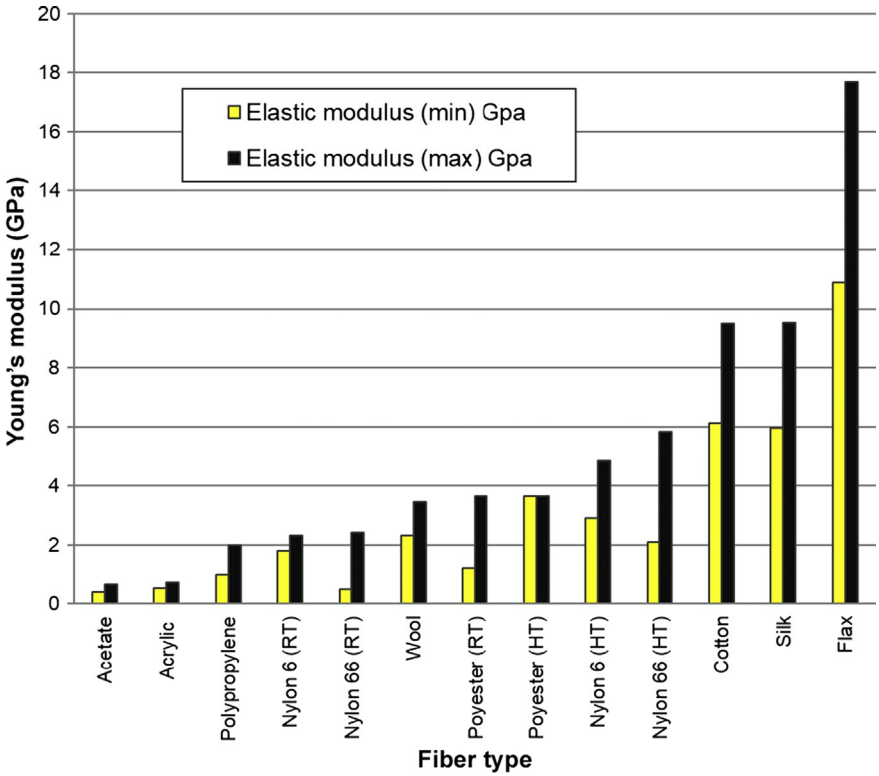


Fig. 8.7 Typical values of Young's modulus of conventional fiber types.
Graph developed from data of J. Gordon Cook, Handbook of Textile Fibers: Vol. II: Man-Made Fibers, Woodhead Publishing Limited, Cambridge, 2009 (Reprinted 1993, 2001, 2002); J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; J.W.S. Hearle, R.H. Peters, Fiber Structure, The Textile Institute, Butterworths, 1963; B. Lomas, J.W.S. Hearle, W.D. Cooke, Atlas of Fiber Fracture and Damage to Textiles, The Textile Institute, Woodhead Publishing Limited Cambridge, England, 1998; R.R. Franck, Bast and Other Plant Fibers, The Textile Institute, Woodhead Publishing Limited, England, 2005; W.S. Morton, J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962; Y. Elmogahzy, Engineering textiles, in: Integrating the Design and Manufacture of Textile Products, first ed., Woodhead Publishing (Elsevier), UK, 2009; I. Block, Manufactured Fiber, AccessScience@McGraw-Hill, 2002, doi:10.1036/1097-8542.404050, http://www.accessscience.com, last modified: May 6; W. Klein, Man-Made Fibers and Their Processing, The Textile Institute, Manchester, 1994.

uncontrollable flow of material during manufacturing. Fibers may also be blended with other fibers, or they may be bonded with nonfibrous materials. This requires an optimum surface cohesion of fibers.

In closing this section, it is important to point out that the fiber-related aspects discussed earlier represent key design factors that should be taken into consideration in any product development project involving fibrous products. Understanding these

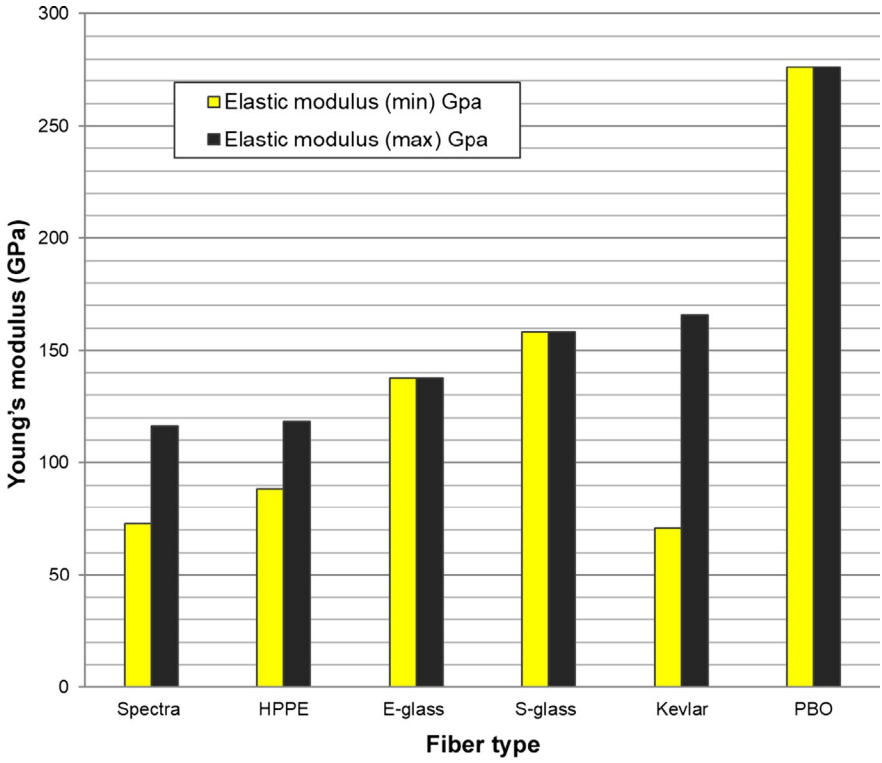


Fig. 8.8 Typical values of Young's modulus of specialty fiber types.
Graph developed from data of J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; T. Hongu, G.O. Phillips, New Fibers, second ed., Woodhead Publishing Limited, 1997.

aspects can assist a great deal in exploring possible solutions to design problems. In addition to these aspects, design engineers should refer to the plausible ranges of various fiber characteristics available in the literatures or fiber producer documents. Fig. 8.13 provides a summary of the key fiber attributes that can influence the performance characteristics of fibrous products. In recent years, nanotechnology has introduced a new category of fibers called "nanofibers." In comparison with the microdenier fiber, which has a diameter of few microns, a nanofiber will have a diameter of less than 1 micron. This three-to-four-atom thick fiber will add new dimensions to the uniqueness of fiber attributes in comparison with those of other categories of material. In addition, it will allow a dominant use of fibers in critical applications such as precision medical products, electronics, precision filters, smart garments, composite, insulation, aerospace, capacitors, transistors, drug delivery systems, battery separators, energy storage, fuel cells, and information technology [22, 23].

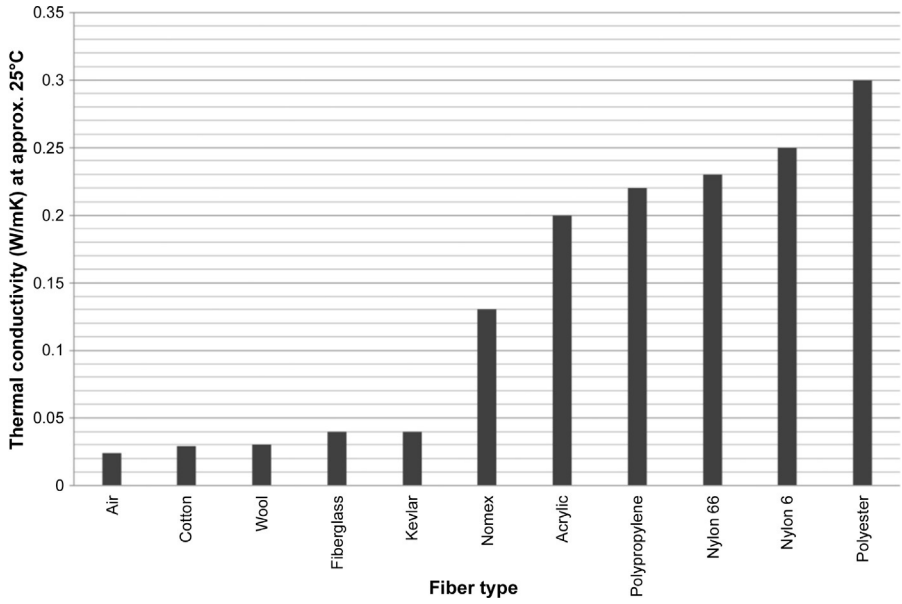


Fig. 8.9 Typical values of thermal conductivity of some fibers.1 Btu ft/(h·ft^{2}·°F = 1.730735 W/(m K).
Based on data from R.B. Seymour, Engineering Polymer Sourcebook, McGraw-Hill, NY, 1990; W.F. Smith, Materials Science and Engineering, AccessScience@McGraw-Hill, 2001, doi:10.1036/1097-8542.409550. http://www.accessscience.com, last modified: May 4; C.E. Carraher, Jr., Polymer, AccessScience@McGraw-Hill, 2004, doi:10.1036/1097-8542.535100. http://www.accessscience.com, last modified: March 12.

8.3 Review of different fiber types

Discussions on fiber types and their associated properties can be found in many literatures. For conventional fibers, an important classic book recommended is titled *Physical Properties of Textile Fibres* by Morton and Hearle [8]. This book covers many of the fundamental aspects associated with both the internal structures and the properties of conventional fibers. For synthetic fibers, technology, and properties, there are many sources of information including the ones listed in the references of this chapter [13, 14, 24–26]. For information regarding specialty fibers, fiber producer's technical reports obtained from their websites are recommended. In addition, some books were published that dealt specifically with specialty fibers [3, 15]. In this section, only a brief review of different fibers is presented as a quick reference for the reader.

8.3.1 Natural fibers

Natural fibers are those of natural sources, vegetable, or animal origins. Examples of the former include cotton, flax, and jute. Examples of the latter include wool and camel hair. Key points in dealing with these fibers in a product development project are as follows [16]:

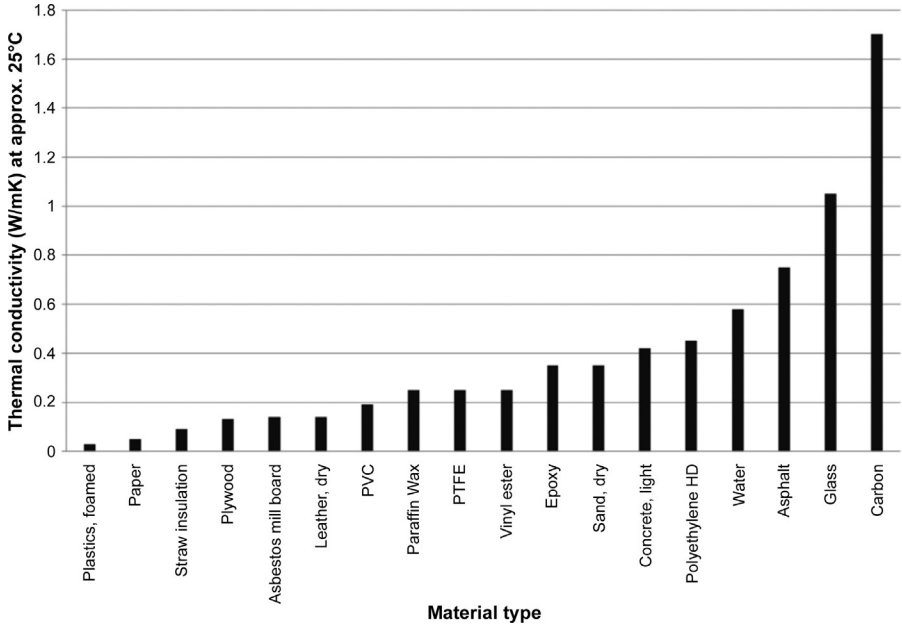


Fig. 8.10 Typical values of thermal conductivity of some materials.
Based on data from R.B. Seymour, Engineering Polymer Sourcebook, McGraw-Hill, NY, 1990; W.F. Smith, Materials Science and Engineering, AccessScience@McGraw-Hill, 2001, doi:10.1036/1097-8542.409550. http://www.accessscience.com, last modified: May 4; C.E. Carraher, Jr., Polymer, AccessScience@McGraw-Hill, 2004, doi:10.1036/1097-8542.535100. http://www.accessscience.com, last modified: March 12.

- Natural fibers are typically discrete (or staple fibers), and they are naturally produced of a wide range of fiber length, diameter, strength, and flexibility even within the same type of fibers.
- Natural fibers being unmanufactured and naturally produced will exhibit high degree of inherent variability in their properties. As a result, they should be described by both average values and associated variability measures such as range or variance.
- The inherent variability in the properties of natural fibers requires a great deal of effort in fiber selection and elimination of extreme undesired values.
- Blending of natural fibers, either within the same fiber type or of different fiber types, represents a key design aspect.
- Some properties of natural fibers (e.g., strength and color) may not exhibit linearly additive patterns upon blending. Therefore, experimental blending analysis is often critical in using natural fibers.
- When natural fibers are blended with synthetic fibers (e.g., cotton and polyester), the issue of linear additivity of fiber properties becomes more critical, and a great deal of experimenting may be required to reach optimum blends.
- Natural fibers will typically have low flame resistance, and they burn when ignited. Therefore, using these fibers in fire-retardant products will require special chemical treatments.

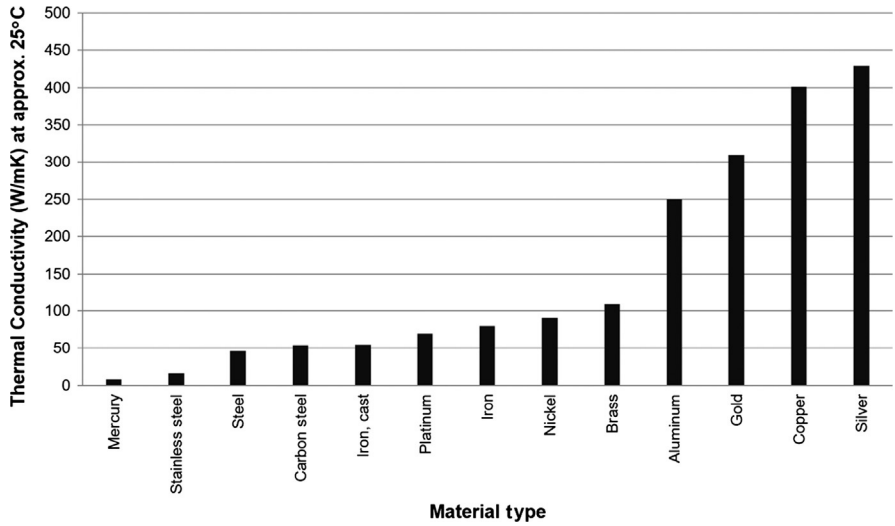


Fig. 8.11 Typical values of thermal conductivity of highly conductive materials. Based on data from R.B. Seymour, Engineering Polymer Sourcebook, McGraw-Hill, NY, 1990; W.F. Smith, Materials Science and Engineering, AccessScience@McGraw-Hill, 2001, doi:10.1036/1097-8542.409550. http://www.accessscience.com, last modified: May 4; C.E. Carraher, Jr., Polymer, AccessScience@McGraw-Hill, 2004, doi:10.1036/1097-8542.535100. http://www.accessscience.com, last modified: March 12.

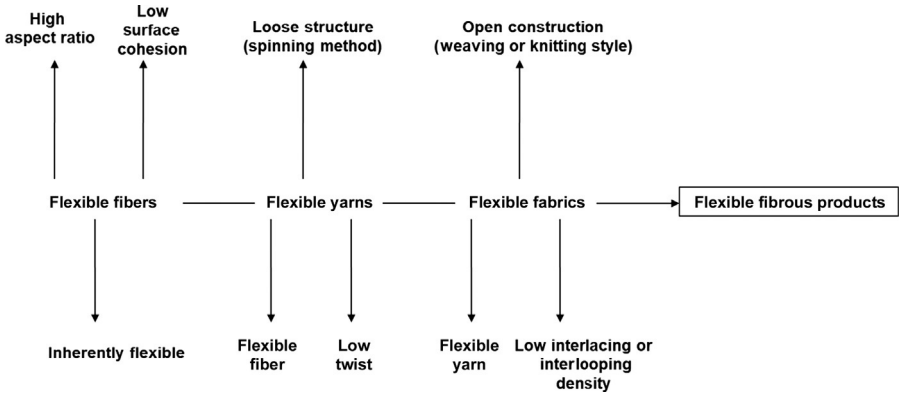


Fig. 8.12 Main factors determining flexibility of fibrous products.

8.3.1.1 Cotton fibers

Cotton is a natural cellulosic fiber made from long chains of natural cellulose (carbon, hydrogen, and oxygen). It exhibits a long linear molecular chain of over 10,000 cellulosic units held together with strong intermolecular forces [4, 8, 19]. As a result, it is reasonably strong within its use boundaries. The length-to-diameter ratio of the fiber is in the order of several thousand, which provides a great deal of flexibility, processing

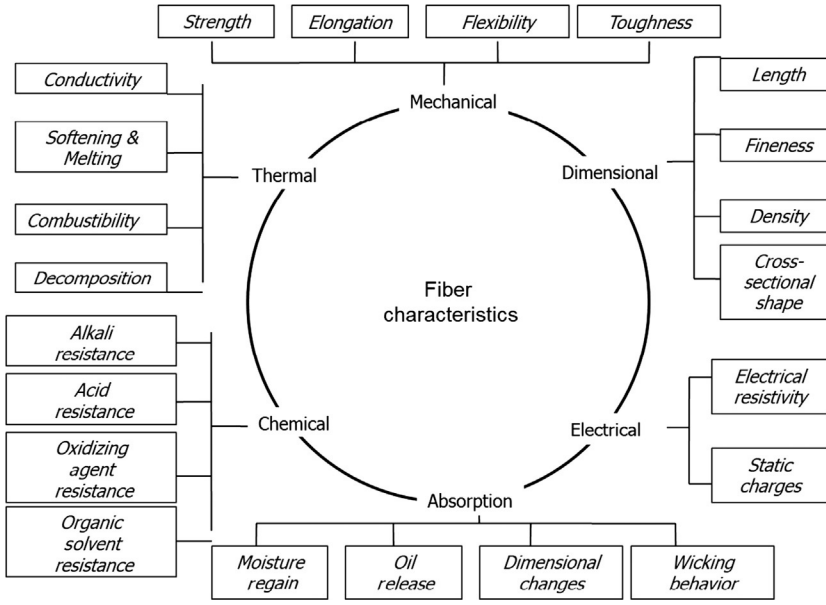


Fig. 8.13 Common performance-related fiber attributes.

ease, and product good-wearing performance. A typical cotton fiber length may range from 0.90 to 1.5 in., and fiber fineness may range from 100 to 200 millitex (0.9–1.8 denier). Most cotton fibers exhibit a range of fiber bundle tenacity from 25 to 35 g_f/tex (or 2.7–3.9 g_f/denier). Extralong staple (ELS) cotton can exhibit higher tenacity of up to 40 g_f/tex (4.4 g_f/denier). Cotton fiber breaking elongation typically ranges from 4% to 6%.

Most cotton fibers are used in traditional fibrous products, particularly apparels. This is due to their natural appeal and esthetic properties. Cotton fibers are also used widely for household and interior products such as towels, sheets, pillowcases, bedspreads, tablecloth, and upholstery. In recent years, efforts have been made to use cotton in technical fibrous products such as fire-resistant clothing and commercial carpets. In these applications, cotton fibers are treated with chemicals to enhance their performances. For example, chemical treatments such as Proban and Pyrovatex are used to make cotton fire-retardant products [27, 28]. In addition, cotton may be blended with wool and low-melt polyester fiber for utilization in carpets without the need of any topical finish.

8.3.1.2 Bast fibers

Another group of cellulosic fibers is Bast fibers or long-vegetable fibers. These include [29] flax, hemp, jute, and ramie. These fibers are relatively coarse, and they exhibit high levels of durability. Flax (also called linen) is the most commonly used fiber of this group. It is used to make a variety of apparel products including dresses, skirts, blouses, suits, coats, and hats. It is also used in interiors and home furnishing

products such as draperies and upholstery fabrics. Although flax exhibits approximately the same degree of polymerization as cotton, it is stronger than cotton as a result of its higher molecular orientation and higher crystallinity (see Table 8.1 and Fig. 8.3). It has a tenacity of about 6 g_f/denier and elongation at break from 1.5% to 3.5%. Like cotton, flax is stronger in wet conditions than in dry conditions (approximately 20% stronger).

Hemp is another long-vegetable fiber that was once the principal fiber used for marine cordage until replaced by abaca and sisal. It is still used extensively for twine and for many of the same products as linen. The fiber is usually about 4–7 ft (1–2 m) in length and 22 micron diameter. It is typically spun into coarser and strong yarns. The ends of the fibers are blunt and very thick walled, and they show some branching. This branching distinguishes hemp from linen under the microscope.

Jute fiber is commonly used for making strong and bulky fabric or twine that are used in wrapping or bag materials (e.g., Hessian, known as burlap in the United States, and a heavier weight fabric known as sacking). Jute fiber is usually 5–10 ft (1.5–3 m) or more in length and 20 micron diameter. Synthetic fibers, especially polypropylene, have made substantial inroads in the markets for jute. Polypropylene bags and prime back for tufted carpeting have displaced large quantities of jute. Also, bulk handling has eliminated much of the former market for grain bags, especially in the United States. Another competing fiber to jute particularly in products such as sacks, bags, and paper is kenaf. This is a long-vegetable fiber that has a similar appearance to jute, although the fiber is somewhat lighter in color. It also has similar or slightly lower strength than jute.

Ramie fiber is produced in length ranges from 28 to 60 in. (70–150 cm), and it can have up to 50 micron diameter. Ramie fabrics are typically very strong and stiff. They also gain strength when wet and are highly resistant to mildew and rot.

8.3.1.3 Wool fibers

Wool fiber is another common type of fibers used in traditional fibrous products. It is typically more expensive than cotton, and it is of limited supply as it primarily comes from the fleece of sheep. As an animal fiber, the main component of wool is protein (called keratin), which has a polypeptide chain with amino acid side chains. Keratin has a helical chain structure with strong hydrogen bonding [8]. The surface of the fiber has a unique surface morphology characterized by overlapping scales extending lengthwise from the cuticle. These scales provide a "differential frictional effect" with friction against the scales being significantly higher than that in the direction of the scales. Wool fibers may have fineness (diameter) ranging from 10 to 30 microns and fiber length ranging from 1 to 3 in. Coarse wool fibers can be stiff causing irritation and prickling effect when projecting from the fabric against the human skin. When wool fibers are used in carpets, this stiffness may provide a positive effect in terms of carpet integrity. The tenacity of wool fibers can vary significantly depending on the type of wool used; a typical range may be from 1.8 to 2.0 g_f/denier. Fiber elongation also varies from 25% to 45%. This high extensibility has a positive effect on its comfort characteristics. Like cotton, wool fibers are mostly used in

apparel products such as men's suits, women's suits and dresses, coats, casual shirts, and scarves or hats. More than 10% of the wool fibers are used for carpets and rugs. It also holds a place in household products such as blankets and upholstery.

8.3.1.4 Silk fibers

Silk is another protein natural fiber used in making traditional fibrous products, particularly luxury apparel products. It is produced by the silkworm and is the only naturally produced continuous filament, but it can be used in staple form. In the context of durability, silk is stronger than wool but is also stiffer. This strength is a direct result of high degree of polymer orientation and high crystallinity enhanced by strong hydrogen bonding. Although silk has long-chain molecules as its backbone, there are various sorts of side chains attached to these. One of the major problems of silk, which directly influences the performance characteristics of silk products, is its low crease resistance. This problem is typically handled by epoxide treatments [30].

8.3.2 Regenerated man-made fibers

Regenerated man-made fibers represent a unique category of fibers that is likely to attract more attention in product developments in the years to come because of their high sustainability. They are man-made fibers but made from natural resources, and they require lower energy (less use of fossil fuels). Regenerated fiber wastes can easily be used as a secondary raw material in producing new products. In the context of product development, the uniqueness of regenerated fibers stems from key characteristics such as high absorption, washability, softness, smoothness, tactile comfort, and good drape. New developments in the fiber industry have resulted in many derivatives of regenerated fibers with better physical properties (e.g., high tenacity and high wet modulus viscose). Viscose, rayon, acetate, triacetate, modal, Tencel, and Lyocell are all regenerated fibers. Regenerated fibers are mostly used in apparel products such as blouses, shirts, dresses, and slacks and lining fabrics for suits and coats.

Viscose rayon is a dominant regenerated fiber. In Chapter 2, the story of rayon development was introduced; it marked the beginning of unlimited development of man-made fibers. In comparison with cotton, conventional viscose rayon exhibits inferior physical properties as a result of its lower degree of polymerization and lower crystallinity. Regular viscose rayon fibers have medium strength, low modulus, and high elongation. Viscose fibers can be used as a filament yarn, woven or knitted into lustrous fabrics and crepe fabrics, and as a staple fiber, which can be blended with other fibers to add luster and absorbency.

Acetate fibers are made from cellulose acetate polymer solution. This fiber is relatively less durable than other fibers as it exhibits poor strength and poor abrasion resistance. Tencel and Lyocell are made, so they are fully recyclable and biodegradable; high strength when wet, minimal shrinkage, and good dye absorbency make them a popular blended fiber. Lyocell can also be used as a nonwoven fabric for wipes and swabs in medical situations and even for a disposable gown for medical staff.

8.3.3 Synthetic fibers

A wide range of synthetic fibers (oil and coal based) are used in making traditional fibrous products [13, 14]. The most commonly used fibers are polyester, nylon, acrylic, and polypropylene fibers. These fibers offer a wide range of values of different durability levels giving unlimited opportunities for designers of traditional fibrous products to select desirable levels of mechanical properties and other important characteristics. For example, melt-extruded fibers such as nylon 6,6 and nylon 6 are made in a wide variety of fiber fineness and cross-sectional shapes that are suitable for different types of traditional fibrous products. These fibers can be drawn at different draw ratios leading to different levels of strength and elongation. They are superior in elastic recovery and dimensional stability to many of the natural or regenerated fibers. A significant amount of nylon fibers is used for carpet and rug products; a relatively small amount is used for apparel products such as hosiery and socks, underwear, and nightwear. Nylon fibers can be made of regular tenacity suitable for apparel products or high tenacity suitable for the carpet market (see Tables 8.2 and 8.3).

Polyester fiber is also produced by melt spinning. This fiber is defined as any long-chain synthetic polymer composed of a least 85% by weight of an ester of a substituted aromatic carboxylic acid, including but not restricted to substituted terephthalate units and para-substituted hydroxybenzoate units. This fiber enjoys excellent strength and good elongation properties. The fact that this fiber can be effectively and efficiently blended with cotton provided a great market share in apparel and household products. Polyester has lower elastic recovery than nylon when elongated at 3%. As a result, nylon is more appealing for products such as women's sheer hosiery, and polyester is more appealing in durable clothing [29].

Acrylic fibers exhibit wool-like properties that make them attractive in the apparel market. They are known as manufactured fibers in which the basic substance is a long-chain synthetic polymer composed of at least 85% by weight of acrylonitrile units. These are spun into fibers by dry- or wet-spinning methods. Acrylic filaments are commonly converted into staple fibers for apparel products. They exhibit slightly higher tenacity and higher toughness than wool fibers. They also exhibit higher elastic recovery, which adds to their appeal in the apparel market. Indeed, over 75% of acrylic products are in the apparel market (e.g., sweaters, high-pile fleece for coats, and hosiery). Acrylic fibers also hold a solid place in the household and interior markets with products such as blankets, draperies, and upholstery.

Polyolefin fibers are commonly known as manufactured fibers in which the basic component is any long-chain synthetic polymer composed of at least 85% by weight of ethylene, propylene, or other olefin units [13]. They include polyethylene and polypropylene made by addition polymerization of ethylene and propylene and subsequent melt extrusion, respectively. Polyethylene fiber typically has low tenacity and low melting point (110°C). It is available in coarse deniers for some applications such as blinds, awnings, curtains, and car interiors. Polypropylene fibers, on the other hand, are widely accepted in the traditional market. They have high melting point of about 170°C, an average tenacity of 4 g_f/denier, and high breaking elongation. These properties enhance the polyolefin position in the carpet and rug industry and in many industrial applications [13].

Finally, a special category of fibers that has received increasing popularity in recent years is the elastomeric fiber. This is defined as the material that at room temperature can be stretched repeatedly to at least twice its original length and, upon immediate release of the stretch, will return to its approximate original length [13, 24, 25]. With at least 85% segmented polyurethane in their structure, elastomeric fibers are never used as the sole component of a product; instead, they typically play a supporting role by adding elastic features to fancy yarns and apparel products. The most common type of elastomeric fibers is spandex (commercially known as Lycra). This fiber is typically in a filament form of deniers ranging from 20 to 5400 denier. In the context of durability, spandex has lower tenacity than most fibers, but its high elongation and superior elastic recovery make it usable in many apparel products.

8.3.4 Fibers for high-performance applications

High-performance fibers represent a special category of fibers that is primarily made for technical products, but it can be used for some traditional fibrous products (e.g., some apparel support, upholstery, and floor coverings). From a design viewpoint, high-performance fibers provide additional design options in many products. They can be used in many fields from ground transportation to aerospace and from biotechnology to computer and communication applications. The key criteria of high-performance fibers are [31–36] very high strength, exceptionally high-temperature resistance, and unique geometrical characteristics (surface morphology and cross-sectional shapes). These criteria have been a result of major advances in polymer and fiber technology. Examples of high-performance fibers are discussed in the succeeding text. The reader should refer to Table 8.4 and Figs. 8.1, 8.4, 8.5, 8.8, and 8.10 for typical values of the characteristics of high-performance fibers.

8.3.4.1 Aramid fibers

Aramid fibers are polyamides, where each amide group is formed by the reaction of an amino group of one molecule with a carboxyl group of another. However, the presence of aromatic rings makes them more stable than with the linear arrangements of atoms. This provides great strength and heat stability. Two of the traditional aramid fibers are Kevlar, a high-strength fiber, and Nomex, a heat-resistant fiber. Kevlar was first produced by E.I. Du Pont de Nemours & Company, Inc. in the early 1970s as a candidate fiber for reinforcing tires and some plastics. Shortly after, this lightweight, strong, and tough fiber was incorporated in many products including composites, ballistics, tires, ropes, cables, asbestos replacement, and protective apparel [31]. Some radial automobile tires reinforced with Kevlar cords are like those reinforced with steel. Over the years, other Kevlar-like fibers were introduced such as Twaron by Accordis BV and Technora by Teijin Ltd.

Kevlar is commonly called para-aramid or poly(*p*-phenylene terephthalamide). It belongs to a class of materials known as liquid crystalline polymers [31]. In contrast with conventional flexible polymers, which in solution, they can easily bend and entangle (forming random coils), Kevlar polymers are very rigid and rodlike. As a result, in solution, they can aggregate to form ordered domains in parallel arrays.

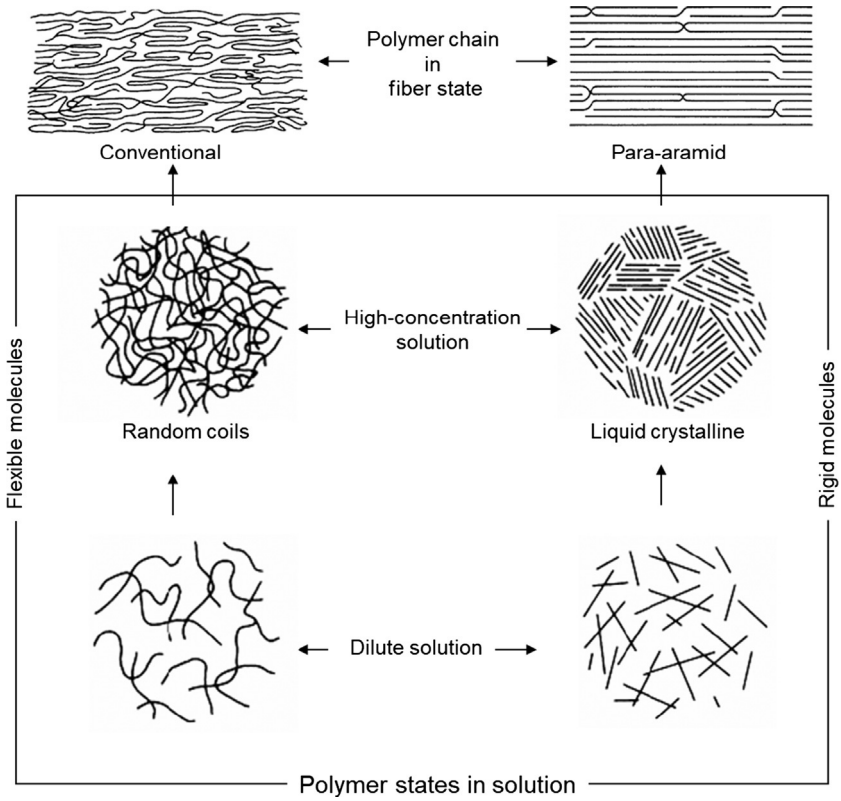


Fig. 8.14 Comparison of fibers from conventional flexible polymers and rigid polymers.

Fig. 8.14 shows comparison of fibers from conventional flexible polymers and rigid polymers. When the polymer solution (in concentrated sulfuric acid solvent) is extruded through a spinneret and drawn through an air gap during fiber production, the liquid crystalline domains are oriented and aligned in the direction of flow, yielding an exceptional degree of alignment of long, straight polymer chains parallel to the fiber axis. The final structure is an anisotropic, high strength, high modulus along the fiber axis. It is also fibrillar, which has a profound effect on fiber properties and failure mechanisms. Subsequent high-temperature processing under tension can further increase the orientation of the crystalline structure and result in higher fiber modulus. Kevlar fiber can be of continuous filament form or staple fiber form. This makes it formable into spun yarns, woven or knit fabric forms, textured yarn, needle-punched felts, spun-laced sheets, and wet-laid papers.

Nomex is the registered brand name of a flame-retardant meta-aramid material. This *m*-aramid or poly(*m*-phenylene isophthalamide) was first discovered by DuPont in the 1970s. The DuPont scientist responsible for discoveries leading to the creation of Nomex is Dr. Wilfred Sweeny. This unique material can be made in either sheet or fiber form. Nomex sheet is a calendered paper commonly used for electrical insulation

applications such as circuit boards and transformer cores and fireproof honeycomb structures where it is saturated with a phenolic resin [3]. These honeycomb structures and mylar-nomex laminates are used extensively in aircraft construction. In addition, both the firefighting and vehicle racing industries use Nomex fibers to design clothing and equipment that can withstand intense heat.

Although Nomex belongs to the class of aramid fibers like Kevlar and both are largely heat and flame resistant, Kevlar having a para-orientation can be molecularly oriented and aligned to provide exceptionally high strength. Meta-aramid, or Nomex, on the other hand, cannot be aligned during filament formation. As a result, it has lower strength and modulus than Kevlar. Under exposure to extreme heat, Nomex structures consolidate and thicken. When blended with a small percentage of Kevlar, a combination of high-temperature resistance and strength enables these swollen fabrics to remain intact. This is referred to as nonbreak-open protection [3, 15]. Another key attributes of Nomex is its light sheet weight (as low as 1.5 oz per square yard). This makes it possible to design fabrics and protective garments and gloves for various applications. It also extends its applications to areas such as reinforcement fabric in diaphragms and hose constructions. The fiber is also highly resistant to hydrolysis, alkali, and oxidative substances. This makes it an excellent candidate for a premium class of fabrics used for rubber reinforcement. Additional good attributes of Nomex is low shrinkage and good dye affinity.

Examples of Nomex products include Nomex hoods used as a common piece of firefighting equipment [31, 32]. This piece is typically placed on the head on top of a firefighter's face mask to protect the portions of the head not covered by the helmet and face mask from intense heat and fire. Race car drivers use similar hood to protect them in the event of fire engulfing their cars. Military pilots and aircrew wear one-piece coveralls (or flight suits) made of about 90% Nomex to protect them from the possibility of cockpit fires. The remaining 10% is usually Kevlar thread used to hold the fabric together at the seams. The US space program also used its share of Nomex and Kevlar, particularly for the extravehicular mobility unit and ACES pressure suit. These items require high fire resistance and high protection against extreme environmental conditions such as water immersion to near vacuum. Other Nomex products include thermal blankets on the payload bay doors, fuselage, and upper wing surfaces of the space shuttle orbiter.

8.3.4.2 Gel-spun polyethylene fibers

This category of fibers represents ultrastrong and high-modulus material derived from the simple and flexible polyethylene molecule. They are commonly called high-performance polyethylene (HPPE) fibers, high-modulus polyethylene (HMPE) fibers, or sometimes extended chain polyethylene (ECPE) fibers [33]. The molecular structure of this category of fibers is different from that of para-aramid fibers in that it is not a rodlike structure, which needs to be oriented in one direction to form a strong fiber. Instead, polyethylene has much longer and flexible molecules that, by physical treatments, can be forced to assume straight (extended) conformation and orientation along the fiber axis [34].

In the real world, polyethylene is probably the most commonly used polymer (or plastic) that human uses in daily life. This is the polymer that makes grocery bags, shampoo bottles, and children's toys. For such a diverse application, the normal polyethylene polymer has a very simple structure, the simplest of all commercial polymers. It is nothing more than a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom. In this simple form, the molecules are not oriented and can easily be torn apart. As a result, the formation of high-strength polymer requires stretching, orienting, and forming a highly ordered (crystalline) structure from a long molecular chain. Accordingly, the starting substance should be polyethylene with an ultrahigh molecular weight (UHMW-PE). This, in turn, creates a problem with spinning since extrusion of a very high-viscosity melt is extremely difficult. Drawing the filaments for high orientation is also difficult as a great deal of entanglement of the molecular chains is to be expected with this type of polymers. These two problems were solved using the so-called gel spinning [33]. In principle, gel spinning operates on the basis of dissolving the molecules in a solvent prior to extrusion through a spinneret [33, 34]. This only allows a smooth extrusion, but molecular entanglement has to be resolved through superdrawing of the gel material after spinning. Fig. 8.15 shows the basic difference between normal PE and HPPE.

The most common types of high-performance polyethylene fibers are Dyneema and Spectra. These are produced as multifilament yarns of a wide range of denier per filament (dpf) from 0.3 to 10 dpf. The tenacity of a single filament can be greater than 3 N/tex, and the modulus can be greater than 120 N/tex (see Table 8.4). Since fiber density is less than one, the fiber can float on water. The combination of high tenacity and low density makes the specific strength of this fiber higher than steel (10–15 times that of good quality steel). The modulus of high-performance polyethylene fiber is second only to that of special carbon grades. Elongation at break is relatively small, which is common in most high-performance fibers. However, the high tenacity makes these fibers extremely tough as indicated by their high values of energy to break [34]. The fibers are also highly resistant to abrasion, moisture, UV rays, and chemicals.

The Dyneema fiber, developed by the Dutch company DSM, has been used in many high-strength, low-weight applications. These include bulletproof armor and protective clothing for law enforcement and military personnel. Some body armors

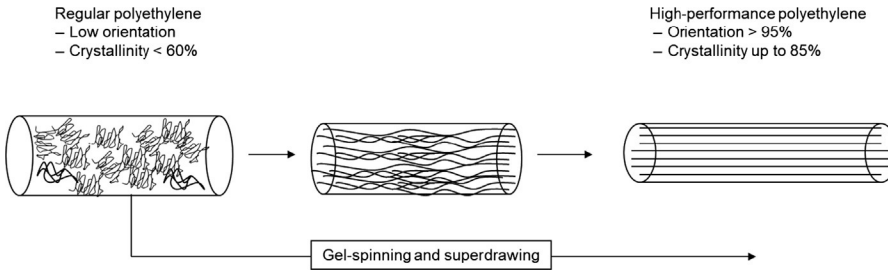


Fig. 8.15 Comparison of molecular structures of normal PE and HPPE.

have been designed from a combination of Dyneema high-performance polyethylene fiber and Steelskin steel cord material to provide stab protection against edged weapons, an application that traditionally required heavier and stiffer outfits, which were uncomfortable to use. The underlying design principle of this product is based on blunting and damaging a blade with each thrust using the steel wire while further absorbing the impact energy by the superstrong fiber to stop the damaged knife and minimize trauma (https://www.army-technology.com/contractors/personal/dsm-dyneema/).

The Spectra fiber produced by Honeywell has also been used in protective clothing (or shield technology), https://www.packagingcomposites-honeywell.com/spectra/product-info/spectra-fiber/. Shield technology lays parallel strands of synthetic fiber side by side and holds them in place with a resin system, creating a unidirectional tape. Two layers are then cross plied at right angles (0/90 degrees) and fused into a composite structure under heat and pressure. The preconsolidated cross-plied material is then packaged as rolls to make a ready for use product. This technology can use Spectra fiber or other fiber types such as aramid fiber. The distinct advantage of shield technology, especially in armor applications, is that it preserves the strength of the Spectra fiber or any other fiber encased within the resin matrix. Because the fibers are not crimped as they are in a traditional weaving process, the energy of the projectile is allowed to rapidly dissipate along the length of the fiber. Normally, the weaving process induces a great deal of bending and flexing, which reduce the characteristic molecular alignment of the high-performance polyethylene fiber.

8.3.4.3 Carbon fibers

Carbon fibers contain at least 90% carbon by weight. They are commonly derived from several organic polymers, such as rayon and polyacrylonitrile (PAN). The first commercial carbon fiber was rayon based introduced in 1959. This fiber found its applications primarily in military products. Since 1970, PAN-based fibers have largely replaced rayon-based fibers in most applications. This was attributed to their superior tensile strength. PAN-based carbon fibers are now used in a wide array of applications such as aircraft brakes, space structures, military and commercial planes, lithium batteries, sporting goods, and structural reinforcement in construction materials [35]. They can be woven into sheets, tubes, or other desired structures, and they are often used in making carbon fiber composites using epoxy resins or other binders.

Another more advanced carbon fiber is the so-called pitch-based carbon fiber. This is relatively very expensive, but it is unique in its ability to achieve ultrahigh Young's modulus and thermal conductivity. The high cost of this type of fibers has restricted their use to some specific military and space applications. A lower modulus, nongraphitized mesophase pitch-based fiber, of lower cost, was also introduced for extensive use in products such as aircraft brakes. In addition to strength and modulus characteristics, it also exhibits good thermal and electrical conductivity.

PAN-based carbon fibers are made using many different methods [35]. The polymer is made by free-radical polymerization, either in solution or in a solvent-water suspension. The polymer is then dried and redissolved in another solvent for spinning,

either by wet spinning or dry spinning. Melt-spinning PAN plasticized with water or polyethylene glycol is another spinning possibility that is under development. The preferred method for high-strength carbon fiber (i.e., 80% strength improvement over conventional carbon fibers) is wet spinning using clean room conditions followed by heat treatment. Examples of carbon fibers produced by these methods include Toray T800 and T1000. To make carbon fibers, the polymer is stretched into alignment parallel with what will eventually be the axis of the fiber. Then, an oxidation treatment in air between 200°C and 300°C transforms the polymer into a nonmeltable precursor fiber. This precursor fiber is then heated in a nitrogen environment. As the temperature is raised, volatile products are given off until the carbon fiber is composed of at least 90% carbon. The temperature used to treat the fibers varies between 1000°C and 2500°C depending on the desired properties of the carbon fiber. Under these high temperatures, carbon fibers of diameters ranging from 6 to 10 μm can be produced. With a fiber density ranging from 1.75 to 2.0 g/cm^3, fiber strength can range from 3 to 7 GPa, modulus from 200 to 500 GPa, compressive strength from 1 to 3 GPa, and shear modulus from 10 to 15 GPa. Carbon fibers made from pitch can have modulus, thermal, and electrical conductivities as high as 900 GPa, 1000 W/mK, and 106 S/m, respectively.

Graphite fibers can be considered as derivatives of carbon fibers. If during the treatment process of carbon fibers, the temperature is raised above 2500°C, graphite will be formed instead of carbon fibers [36, 37]. However, most of the graphite used in industry is manufactured by heating petroleum by-products to about 2800°C. The petroleum by-products are similar to the polymers used in the carbon fiber process in that both contain chains of carbon atoms. One may consider graphite as a soft form of carbon, which exhibits a unique combination of very low density and high elastic modulus with mechanical strength increasing with increasing temperature. Indeed, this unique material is capable of mechanical service at temperatures of 2200°C (4000°F) or higher. The main problem with graphite is its vulnerability to oxidation since it is essentially a form of carbon.

8.3.4.4 Glass fibers

The art of heating sand and limestone to form a molten liquid has been known from the time of the ancient Egyptians. Since the 1930s, glass has been spun into fiber that is sufficiently pliable to be woven into fabrics. Some believe that Napoleon's funeral coffin was decorated with glass fiber textiles. Glass fibers are prepared by the melt spinning of previously formed glass marbles, and the molten filaments are drawn down to very fine dimensions [38]. Glass fibers are inherently stiff, but they stem their flexibility from fiber fineness. Indeed, the fibers are so stiff that when broken, they can penetrate the human skin, making them unsuitable for use in apparel or upholstery. Because of their good resistance to the degrading effects of sunlight and their flame resistance, they can be used for curtains and drapery. They also provide a nonrotting, nonsettling insulating material for homes and industrial uses.

In Chapter 7, it was indicated that glass fibers have been used as a substitute to asbestos fibers in high-temperature applications because of their high heat resistance

(up to 450°C). From a design viewpoint, the thermal performance of glass fibers is attributed to two key factors: the thermal conductivity of the glass itself (see Fig. 8.10) and the structural features of a fiber glass product (structure density, fiber dimensions, and air/fiber volume ratio). Fiber glass is also commonly used for filtration purposes. For these applications, the surface area of fibers and the structural pore size represent the key design parameters. In this regard, fiber glass can be made of superfine to medium or coarse diameters (0.05–25 μm). For apparel applications, fiber glass has poor esthetic characteristics and high densities and is difficult to process. Another critical field of fiber glass is electronic and communication. For these applications, optical fibers made from fiber glass are extremely effective.

Since silica is an excellent glass base, inorganic glasses are all made from silica. The problem is that silica $(SiO_{4/2})_n$, being a three-dimensional network cannot be converted into a liquid form easily. It fails to exhibit a sharp melting point and starts to soften at 1200°C, but even at this point, it is not fluid enough for extrusion into filaments; this requires a higher temperature of up to 2000°C. Some additives may be used to reduce the melting point of silica [38, 39]. The majority of continuous glass fibers are spun from the so-called E-glass formulation. E-glass fibers can be used as reinforcing materials for resins, rubber, or polymer composites. Some E-glass fibers are used for fire-resistant applications. Another type of glass fiber is the so-called A-glass. This is more economically attractive as it utilizes plate glass scrap, made in a remelt process rather than difficult direct melting. A-glass normally exhibits half the strength of E-glass, and it is commonly used as insulation materials in many thermal or acoustic applications [39]. Another glass formulation is the so-called C-glass, which commonly used to substitute for the deficiency of E-glass in applications requiring better acid and alkali resistance. C-glass may also be used in place of E-glass for the reinforcement of bitumen for roofing mats. For high-strength composite structures, S-glass developed by Owens Corning Fiberglass is commonly used. Other common applications for glass fibers include electrical circuit boards, automobile water-pump housings, and durable pipes.

8.3.4.5 *Metallic and ceramic fibers*

Metallic and ceramic fibers represent a special category of fibers that aims at using the outstanding features of metal alloys and ceramic material in a semiflexible form to allow easier manipulation of these materials in applications requiring their precise and directed incorporation in various structures [40, 41]. Metallic fibers of silver and gold have been used for millennia to decorate fabrics. Today, metallic fibers serve functional and decorative purposes. These fibers are formed by drawing metal wires through successively finer dies to achieve the desired diameter. Although gold and silver are the easiest to draw, modern methods have allowed the manufacture of steel, tantalum, and zirconium fibers [13]. Because they are electrical conductors, metal fibers have been blended into fabrics to reduce the tendency to develop static electrical charges.

The idea of developing ceramic fibers was largely driven by the need for reinforcing ceramic matrix composites in applications where temperatures can be elevated

to above 1000°C. This type of applications required ceramic structures that are fine and flexible for easy manipulation and directed functions. Now, many ceramic fibers (oxide and nonoxide) are available in the market with diameters ranging from 10 to 20 μm. In addition, larger diameters ceramic fibers (over 100 μm) are also available for applications such as gas turbines, heat exchangers, and contaminant walls for fusion reactors [5].

In comparison with organic fibers or even glass fibers, ceramic fibers are uncontested in withstanding high-temperature applications. In comparison with carbon fibers, ceramic fibers will prevail based on the oxidizing and corrosive issues associated with carbon fibers. Carbon fibers will also degrade at temperatures above 300°C. The inherent stiffness of ceramic fibers can limit their formation into fabrics as they must be woven to meet this requirement. However, this manufacturing limitation can be largely overcome using finer ceramic fibers (about 10 μm) to allow enough flexibility for fabric formation.

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Yarns

9

9.1 Yarn classification

A textile yarn may be defined as a long fine fiber strand of parallel continuous filaments or twisted staple fibers. These linear structures can be interlaced or intermeshed into a two-dimensional or three-dimensional woven or knit fabric structures, and they can also be intertwisted into braids, ropes, or cords. A continuous-filament yarn represents a simple structure in which multiple filaments are laid side by side in parallel arrangement. This type of yarns is typically made by extruding polymer liquid through a spinneret to form liquid filaments that are solidified into a continuous fiber strand. As shown in Fig. 9.1, a continuous-filament yarn is commonly called a monofilament yarn when it consists of a single filament or a multifilament yarn when it consists of many filaments. Continuous filaments can also be converted into other structural derivatives via deliberate entanglement or geometrical reconfiguration, using a process called texturizing for the purpose of producing stretchy or bulky yarns [1,2]. Spun yarns, on the other hand, are produced from staple fibers of natural or synthetic sources using a number of consecutive processes such as blending, cleaning, opening, drawing, and spinning to align the fibers and consolidate them into a yarn via twisting or other means [3].

In addition to the previous main classification, yarns can be classified in different ways. They can be classified by structural complexity into single yarns, plied yarns, and cabled yarns as shown in Table 9.1; by the method of fiber preparation into carded, combed, worsted, and woolen yarns as shown in Table 9.2; and by the method of spinning into ring-spun, rotor-spun, air-jet, and friction-spun yarn as shown in Table 9.3. Details of the spinning methods used for producing these yarns are outside the scope of this book, and the reader may refer to previous literatures dealing with this subject [1–6].

The point of classifying yarn into different categories is to emphasize the fact that there is an infinite variety of yarn structures leading to numerous design options depending on the desired physical properties and performance characteristics required in fibrous products. These structures can be produced using innovative polymer technologies, special fiber blends, well-established technologies of spinning preparation, and innovative fiber consolidation techniques. In addition, special yarn types can be produced to meet highly specific functions as will be discussed later in this chapter.

9.2 Yarn specifications

In practice, yarns can be described by many specifications depending on the desired yarn performance during weaving or knitting, fabric type and fabric construction, and end-product performance. Fig. 9.2 illustrates different types of yarn specifications.

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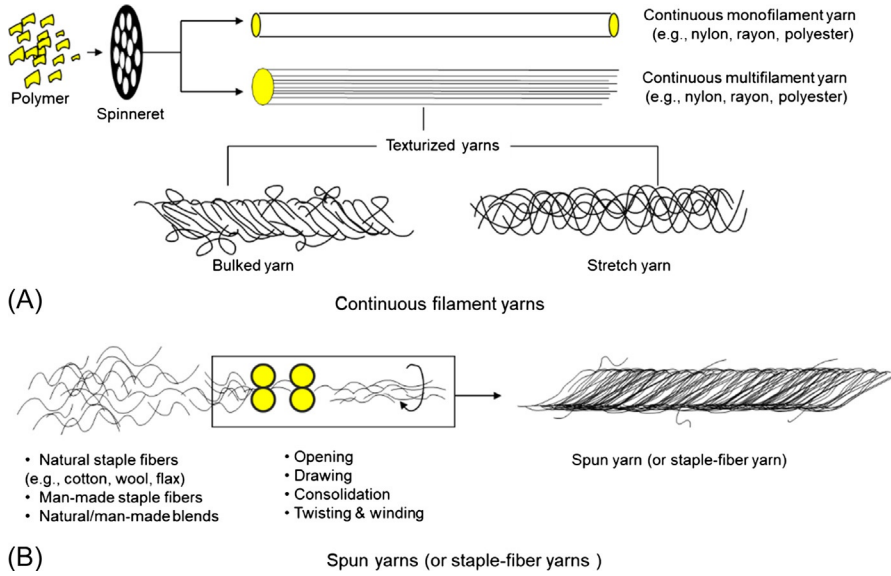


Fig. 9.1 Continuous-filament yarns and spun (staple-fiber) yarns.

Normally, the first specification is yarn type. As indicated earlier, yarns may be classified as spun yarns or continuous-filament yarns. Within each category, there are many types that can also be specified each of which exhibits unique characteristics in relation to the end product as demonstrated in Tables 9.1–9.3. Any yarn type must be associated with the fiber type used or fiber content. This may be 100% of a single fiber type (e.g., 100% cotton or 100% wool) or a blend of two or more fiber types (e.g., 50% cotton/50% polyester yarn). Yarns may also be made of multiple structures such as ply, cords, ropes, compound, and fancy yarns. Yarn type may also be specified by some desired chemical treatments such as mercerization and slack mercerization in the case of cotton yarns, shrink resistance for wool yarns, degumming of silk yarns, delustering of synthetic yarns, and texturing of continuous-filament yarns.

Basic structural parameters of yarns must also be specified. The two structural parameters that are commonly specified for any yarn are count and twist. Ideally, yarn count, also known as yarn size or yarn fineness, should be described by yarn diameter or thickness. However, the difficulty associated with specifying a yarn diameter, due to the high variability in yarn thickness and the deviation from complete roundness in yarn cross section, resulted in using the yarn linear density as an indirect measure of fineness. In general, linear density is defined as the mass per unit length of a fiber, sliver, or yarn. In case of spun yarns, two systems of linear density (or yarn count) are commonly used (see Table 9.4): the direct system, which is based on weight per unit length, and the indirect system, which is based on length per unit weight. Examples of the direct system are “tex” and “denier.” The “tex” system expresses

Table 9.1 Yarn types: by preparation and structural complexity [1–7].

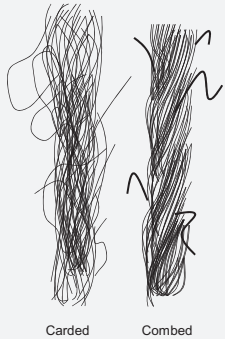
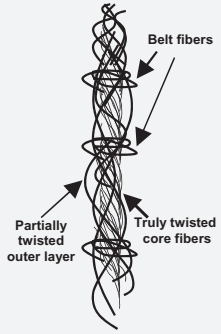
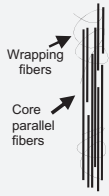
Yarn type	General features
Single yarn 	– A single yarn can be made from continuous filaments, monofilaments, or staple fibers – Continuous-filament yarn basically consists of a monofilament or multifilament arrangement – Staple-fiber (or spun) yarns are made by twisting fibers or by a false-twist technique in which other forms of binding fibers such as wrapping can be used
Plied yarn 	– Plied yarn commonly consists of two single yarns twisted together to form a thicker yarn – A ply yarn may be twisted in the same direction as the single yarn or in opposite direction to add visual and appearance effects
Cabled (multifolded) yarn 	– Several plied yarns can be twisted together to form cabled yarns – Cabled yarns are typically used for heavy-duty industrial applications such as mooring and heavyweight lifting

Table 9.2 Yarn types: by preparation [1–7].

Yarn type	General features
Carded yarn 	– A carded yarn is a single yarn made using cotton processing equipment in which fibers are opened, cleaned, carded, and drawn prior to spinning – It may be considered as an economy yarn as a result of its lower manufacturing cost than a combed yarn (presented in the succeeding text) – The yarn lacks good fiber orientation and has possible moderate to high trash content (when made from cotton) and relatively high neps – It is typically used for coarse-to-medium yarn counts that can be woven or knitted to a wide range of apparel from heavy denim to shirts and blouses
Combed yarn 	– A combed yarn is a single yarn made using the same cotton processing equipment for carded yarn, but with the addition of the so-called combing process – The combing process substantially upgrades the fiber quality and, consequently, the quality of the yarn produced – Combing removes short fibers ($\leq$0.5 in.), remove neps, and reduced trash content to nearly zero. It also results in a superior fiber orientation in the yarn, leading to smoother and softer yarns – Combed yarns are typically upper medium to fine count yarns. They are also more expensive than carded yarns – Combed yarns are typically used for high fashion apparels with comfort and durability representing a unique performance combination
Woolen yarn 	– Woolen yarns are made on the so-called woolen system using basic steps such as the following: fiber selection, dusting, scouring, drying, carding, and spinning – Products produced from woolen yarns include blankets, carpets, woven rags, knitted rags, hand knitting yarn, and tweed cloth
Worsted yarn 	– This is a high-quality yarn made on a series of operations to yield stronger and finer wool yarn quality than that of woolen yarns – Operations involved in worsted yarn include sorting, blending, dusting, scouring, drying-oiling, carding, combing, gilling operation, and drawing – Products produced from worsted yarns include high-quality fashionable wool apparels

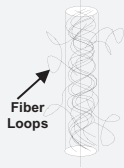
linear density using the weight in grams of 1000 m of yarn, and the "denier" expresses it using the weight in grams of 9000 m of yarn. Examples of the indirect system are the cotton and worsted yarn systems. The cotton system (also called the English count system) is based on the number of 840 yard lengths per pound of yarn, and the worsted system uses 560 yard lengths per pound.

Table 9.3 Yarn types: by spinning system [1–7].

Yarn type	General features
Ring-spun yarns  	– Yarns made on the ring-spinning system – Can be carded or combed – Fibers in the yarn exhibit largely true twist and are taking a helical path crossing the yarn layers – Some fiber points can be in the core of the yarn and others can be in intermediate or outer layers due to the phenomenon of fiber migration – It can be made of a wide range of yarn count and twist – The strongest yarn of all spun yarns – It can exhibit high hairiness and high mass variation – The most diverse yarn type as it can be used in all types of fabric from knit to woven
Compact-spun yarn 	– Yarns made on compact spinning, which is a modified ring-spinning system in which fibers are aerodynamically condensed to reduce hairiness and improve yarn strength – It is commonly used for fine yarns and high-quality apparels
Rotor (open-end) spun yarns  	– Yarns made on rotor spinning – Can be carded or combed – Three-layer structure: truly twisted core fibers, partially twisted outer layer, and belt fibers – It is limited to coarse-to-medium yarn count, and it requires higher twist than ring spun – Relatively weaker than ring-spun yarns but has lower mass variation – It can be used for many knit or woven apparels, but its greatest market niche is denim fabrics
Air-jet spun yarn  	– Yarns made on air-jet spinning, the fastest spinning system – It consists of two layers, core-parallel fibers and wrapping fibers – The yarns exhibit no twist, and the source of strength is the wrapping fibers – Used for many apparel and home products particularly sheets and bed products – It is typically preferred for 100% long staple synthetic fibers or synthetic/natural fiber blends (e.g., cotton/polyester blends)

Continued

Table 9.3 Continued

Yarn type	General features
Friction-spun yarn 	– Yarns made on friction spinning – The yarn exhibits true twisted fibers, but a great deal of fiber loops is presented – It can only be made in very coarse yarn counts used for industrial applications – Largely used for making industrial yarns of different structures including core/sheath yarns – It can be made from a blend of raw fibers and waste fibers

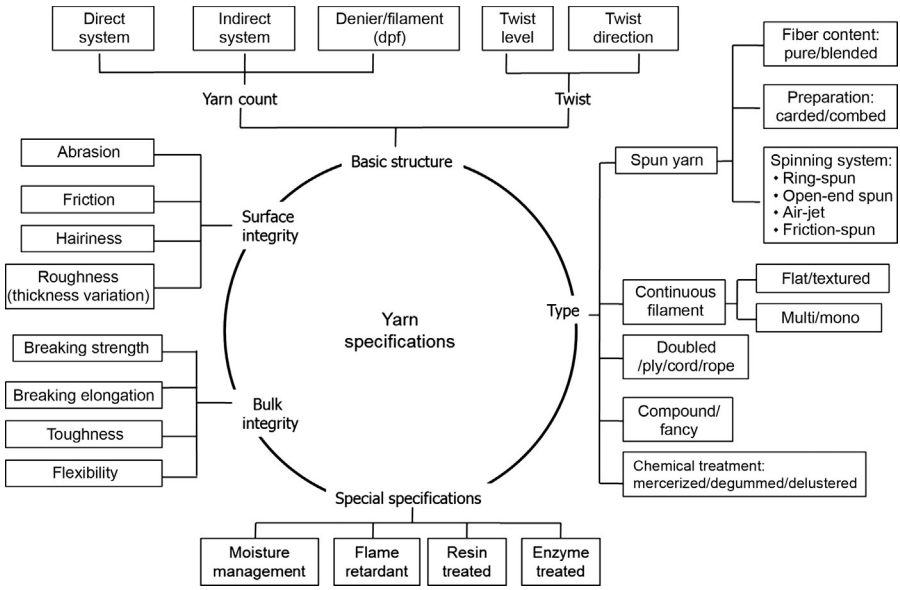


Fig. 9.2 Common yarn specifications.

The number of filaments in a continuous-filament yarn is typically given in conjunction with the yarn count. For example, the designation "80/32" can be used to imply a yarn count of 80 dtex consisting of 32 filaments. This designation indicates that the "dtex" per filament is 80/32 or 2.5. The "tex" system is considered by the ASTM as the universal yarn count system. The "millitex" and the "decitex" units are extensions of the "tex" system that are usually used to describe fiber or filament fineness. For intermediate heavy products such as slivers, the "kilotex" is commonly used.

Table 9.4 Yarn count systems and units [1,3,7].

System	Term used	Common use	Symbol	Unit of count	Equivalent tex
Direct	Tex	Yarns	tex	g/km	1
	Decitex	Yarns	dtex	g/10 km	0.1
	Millitex	Fibers	mtex	g/1000 km	0.001
	Kilotex	Slivers	ktex	g/m	1000
	Denier	Yarns and fibers	den	g/9 km	0.1111
	Grains	Slivers	gr	gr/yd	70.8
Indirect	English (or cotton count)	Yarns and slivers	N_e	840 yd hanks/lb	590.5
	Worsted count	Yarns	Ne_w	560 yd hanks/lb	885.5
	Woolen	Yarns	N_y	256 yd hanks/lb	1938
	Metric	Yarns	Nm	Km/kg	1000

Twisting is a mechanism used to consolidate fibers into yarns and provide yarn strength. Yarn twist is typically described using two parameters: twist level and twist direction. Twist level is commonly expressed by the number of turns of twist per unit length. Another way to express twist level is by using the twist multiplier. These two parameters will be discussed in detail later in the context of yarn structure. Different yarn types will require different levels of twist by virtue of their desired performance and end-use applications. Continuous-filament yarns typically require no twist to impart strength. Nevertheless, small amount of twist (one or two turns per inch) may occasionally be inserted in this type of yarns merely to control the fibers and prevent them from splitting apart. Twist may also be inserted in continuous-filament yarns to avoid ballooning out as a result of accumulating electrical charges [1,6]. In some situations, high amount of twist may be inserted in continuous-filament yarns to break up luster of the yarn or to impart some other effect or fancy attributes [4,6]. However, high twist levels in these yarns can result in deterioration of their strength as discussed later in this chapter.

In spun yarns, twist is necessary to maintain yarn integrity and provide strength. The combination of twist level and twist direction represents a key parameter in the design of yarns or fabrics. Different spun yarns may require different levels of twist. For example, warp yarns used for weaving normally have higher twist levels than weft yarns because of the higher strength required in these yarns. Knit yarns typically have lower twist than woven yarns to provide better softness [7]. Some spun yarns may exhibit very low twist to produce lofty structures. This is typically the case of weft yarns that are to be napped by teasing out the ends of the staple fibers and create soft, fuzzy surfaces [4]. Other spun yarns may exhibit very high twist levels to meet their application needs. These include voile and crepe yarns. Voile yarns

are typically made of high twist to create an intentional stiff feel in the fabric by plying yarns in the same twist direction as the single yarns to increase the total twist. This provides a lightweight stiff furnishing or curtain fabrics that can be made from 100% cotton or cotton blends with linen or polyester. Crepe yarns, also known as unbalanced yarns, have the highest levels of twist. The idea is to create a yarn of high liveliness desired in some apparel products [4].

In spun yarns, fibers may be twisted in clockwise or counterclockwise directions [1]. Commonly, these are described as Z twist or S twist. A single yarn has Z twist if, when it is held in the vertical position, the fibers inclined to the axis of the yarn conform in direction of slope to the central portion of the letter Z. On the other hand, a single yarn has S twist if, when it is held in the vertical position, the fibers inclined to the axis of the yarn conform in direction of slope to the central portion of the letter S.

The importance of twist direction is realized when two single yarns are twisted to form a ply yarn. Ply twist may be Z on Z or S on Z depending on appearance and strength requirements of the ply yarn. When the yarn is woven or knitted into a fabric, the direction of twist influences the appearance of fabric. When a cloth is woven with the warp threads in alternate bands of S and Z twist, a subdued stripe effect is observed in the finished cloth due to the difference in the way the incident light is reflected from the two sets of yarns [4]. In twill fabric, the direction of twist in the yarn largely determines the predominance of twill effect. For right-handed twill, the best contrasting effect will be obtained when a yarn with Z twist is used; on the other hand, a left-handed twist will produce a fabric having a flat appearance [4]. In some cases, yarns with opposite twist directions are used to produce special surface texture effects in crepe fabrics. Twist direction will also have a great influence on fabric stability, which may be described by the amount of skew or "torque" in the fabric [1]. This problem often exists in cotton single jersey knit where knitted wales and courses are angularly displaced from the ideal perpendicular angle. One of the solutions to solve this problem is to coordinate the direction of twist with the direction of machine rotation. With other factors being similar, yarn of Z twist is found to give less skew with machines rotating counterclockwise [1]. Fabrics coming off the needles of a counterclockwise rotating machine have courses with left-hand skew, and yarns with Z twist yield right-hand wale skew. Thus, the two effects offset each other to yield less net skew. Clockwise rotating machines yield less skew with S twist.

Almost all yarn specifications will involve yarn type, count, and twist. In addition, other specifications may be stated depending on the fabric-forming system used and the intended application or end product. These include [1,7] yarn bulk integrity described by physical or mechanical parameters such as strength, elongation, toughness, and flexibility and yarn surface integrity described by yarn hairiness, abrasion resistance, friction, and roughness. For technical fibrous products, yarn types may also be specified in terms of special treatments such as hydrophilic finish, hydrophobic finish, flame-retardant finish, resin treatment, and enzyme treatment [1]. These types of finish will be discussed in Chapter 11.

9.3 Specialty yarns

In some design applications, a more complex yarn may be needed to provide special performance features in the end product. In addition to the common yarn types listed in Tables 9.1–9.3, many specialty yarns can be made to serve some purposes in both traditional and technical fibrous products [8–14]. These yarns are made through manipulation of the basic yarn structures to produce unique physical and appearance features. In the following sections, three types of specialty yarns are discussed: compound yarns, ropes, and fancy yarns.

9.3.1 Compound yarns

A compound yarn typically consists of two or more different fiber strands in a core-wrap structure with the idea being to get a net effect combining the characteristics of the core and the cover components. Many of the core-wrap yarns consist of core filament(s) wrapped or covered by a yarn. These may be categorized as covered-spun compound yarns (see Fig. 9.3A–C). This type of yarn can be produced using the so-called wrap spinning with a hollow spindle [1,4,7–14]. The core being at the inner layer of the yarn typically provides specific bulk characteristics such as exceptional strength (e.g., polyester or nylon filament) or high elasticity (e.g., rubber or spandex). The sheath or the yarn wrap should have a good grip on the core to avoid fiber

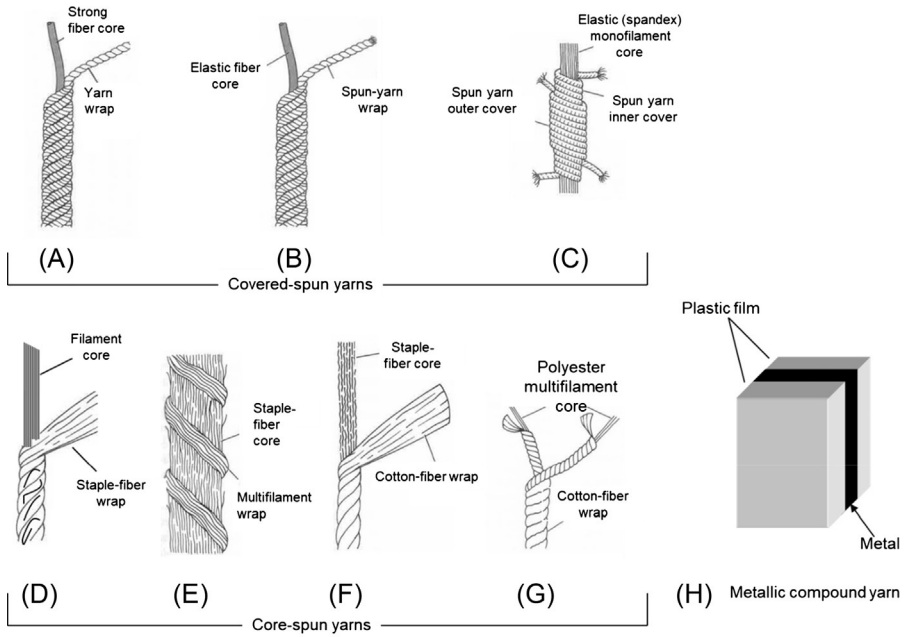


Fig. 9.3 Examples of compound (or composite) yarns [1,4,7].

separation or core slippage. It should also protect the core filament from external adverse effects [1]. This is particularly important when the core filament is elastomeric (e.g., rubber or spandex) as this type of filaments can degrade by exposure to many chemicals or ultraviolet light [13]. In addition, the wrap being in contact with the wearer should exhibit comfort characteristics such as softness, flexibility, and porosity. The wrap yarn can be a spun or filament yarn. In some cases, two wrap yarns may be used with one twisted in the opposite direction to the other, which results in special appearance effects and a good balance against potential yarn snarling.

Another type of compound yarns can be made from a readily separable core surrounded by fibers or fiber strands. These are generally known as core-spun yarns. Different combinations of this type include the following [1,4,7]: filament core/staple-fiber wrap (Fig. 9.3D), staple-fiber core/filament wrap (Fig. 9.3E), and staple-fiber core/staple-fiber wrap (Fig. 9.3F). Most common spinning systems such as ring spinning, air-jet spinning, and friction spinning can be equipped with accessories to produce these types of yarns.

Among the types of core-spun yarns mentioned earlier, the most widely used one is the filament core/staple-fiber wrap yarns. In this yarn, the core consists of continuous filaments surrounded completely by a wrap of staple fibers. It is often referred to as core/sheath yarn since the untwisted staple fibers surrounding the filament core act as a sheath or a casing holding the core. Potential products made from this yarn can range from traditional apparel and household fabrics to technical fibrous products. Examples of these products are as follows [1,4,7–14]:

- Some bed sheets and knit fabrics made from core-spun yarns with polyester filament core and a sheath of combed cotton fibers. The advantages of these products are high strength and durability provided by the polyester filament and comfort characteristics provided by the cotton sheath.
- Some sewing threads made from polyester core/cotton wrap fibers by plying and twisting together two core/sheath yarns.
- Woven corduroy fabric and stretchable denim made from elastomeric core/staple-fiber wrap yarns made from spandex and cotton.
- Some cotton-knit swimsuits made from spandex core and cotton fiber wrap to provide better fit using a very small amount of spandex (as little as 1%). This yields the traditional performance of fabrics made from spun yarns with the additional advantages of good elongation and elastic recovery provided by the spandex component.
- Some secondary carpet backing made from polypropylene split or tape core/polypropylene fiber wrap.
- Flame-retardant and protective clothing made from fiberglass filament core/aramid fibers wrap and carbon core/aramid fiber wrap.
- Protective gloves made with steel wire surrounded by aramid fiber blends.

In view of the previous examples, the idea that a yarn can be made from two or more different components has opened a wide range of opportunities for creative products in many different fields including protective clothing, e-textiles, and optical applications. Now, compound yarns can be made in many different combinations [11–14] such as high-performance fiber core/conventional fiber wrap, metallic wire core/fiber wrap, and optical fiber core/conventional fiber wrap.

The design of compound yarns is likely to face many issues and design problems that should be clearly stated and identified. For example, in the design of staple-fiber core/filament wrap yarns (Fig. 9.3E), untwisted parallel staple fibers (typically 80%–95% by weight) are wrapped by a multifilament strand. Obstacles facing this design typically result from the difficulty of maintaining continuous and consistent streams of staple fibers and the need for precise wrapping [7]. As a result, it is not as widely used as the filament core/staple-fiber wrap yarns discussed earlier. From a functional performance viewpoint, it is yet to be seen whether this type of yarns can provide better compound criteria than the filament core/staple-fiber wrap yarns. However, the design concept of untwisted parallel staple fibers wrapped with multifilament yarns reveals many advantages over the conventional blended yarns. For instance, the absence of twist in the staple-fiber strand should automatically result in a more even yarn diameter than the conventional yarn. The strength and flexibility of the yarn will primarily depend on the wrapping effect. Other merits such as improved abrasion resistance, reduced hairiness, and better pilling resistance can also be realized by virtue of the structure of the yarn. Core-spun yarns made from staple-fiber core/staple-fiber wrap typically have a strand of parallel, untwisted staple fibers completely wrapped with another staple-fiber strand. The need for this type of yarn was a direct result of some of the performance problems associated with filament core/staple-fiber wrap yarns, particularly when normal filament (not elastomeric filament) is used. This structure can easily be produced using conventional spinning systems such as air-jet spinning and friction spinning.

The concept of compound yarn is not restricted to conventional spinning as many innovative techniques can be used to produce other types of compound structures that may be loosely called compound yarns [4]. For example, compound structures can be made from laminated fabrics in which a central core of metal is sandwiched by two layers of plastic films such as nylon (see Fig. 9.3H). The three layers are then passed through squeeze rollers that bind the layers together. Strips of thin films or yarn are then cut and wound onto bobbins [4,7]. This metallic core/plastic cover yarn can be used in many applications, particularly when static charge buildup is to be avoided as the core component will easily conduct electricity. In addition, metallic core yarns with nylon coating have been used in carpeting.

Compound yarns can also be made directly from continuous-filament yarns using multiple polymeric materials that are extruded using different arrangements. Fig. 9.4 shows three examples of these arrangements, namely, side-by-side, sheath-core, and matrix arrangement [4,7]. Each one of these arrangements can provide prespecified functions depending on the polymeric material used. This design concept can obviously provide unlimited options using different types of polymeric materials, different percentage of each type, and innovative polymer arrangements.

Compound yarn should not be treated as fancy yarns, a subject that will be discussed shortly. It is intended to provide unique functional characteristics in end products. In this regard, it is important to mention the technology of friction spinning [3] (e.g., DREF core spinning). This technology has allowed the development of a new range of yarns, including hybrid yarns, high-performance cover yarns, and sewing threads used for technical textiles and in apparel due to their exceptional strength,

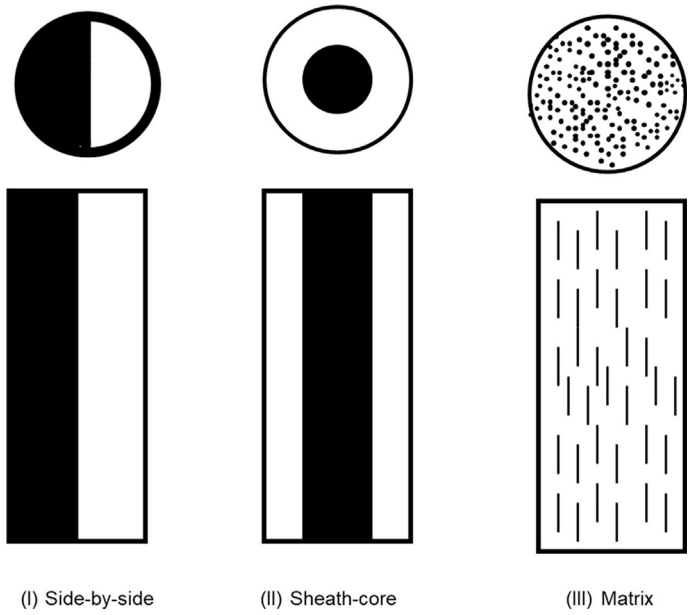


Fig. 9.4 Heterogeneous compound filament yarns [4,5,7].

outstanding abrasion resistance, consistent performance in sewing operations, adequate elasticity for stretch requirements, excellent resistance to perspiration, and ideal wash and wear performance [12]. Compound yarns also opened the door for more use of wool fibers to produce woolen textiles that are finer and lighter than traditional fabrics. In this regard, worsted core spinning can break through the count limit of the traditional wool spinning process by changing the yarn structure to achieve finer and lighter wool fabrics. It uses a filament yarn and a wool roving, which are fed separately and kept a fixed distance from the nip of the front drafting roller, and they make up a triangular zone that is twisted together to form worsted core-spun yarn [13]. A core-spun yarn consisting of a metal filament core and a carbon nanotube (CNT) sheath was constructed for application in two-ply yarn supercapacitors [14] where the core/sheath-structured CNT yarn can be manufactured on a flyer spinner. Because of the very large width of the CNT web in relation to the diameter of the metal filament, the core is completely covered by the CNT sheath in the resultant core-spun yarn. These examples represent what can be categorized as function-focus yarns, which is a yarn primarily intended for specific technical applications via the choice of appropriate fibers or filament and the formation of structural arrangements that directly serve the purpose of the technical application in question. This category of yarn may primarily be driven by the unique functional features of the fibers or filaments used, or it may represent a combination of fiber type and yarn structural arrangement targeted toward specific functional performances such as protective clothing or thermoplastic composites.

9.3.2 Ropes

The general structure of a rope is shown in Fig. 9.5A. The basic component is a single yarn made from staple fibers or continuous filaments; single yarns are plied and twisted together to produce rope yarns; many rope yarns are arranged in helical layers to produce a rope strand; finally, groups of strands are laid together to form the finished rope [15]. The term laid indicates that the individual strands are not simply twisted together but rather revolving in a planetary pattern to form the final rope. Ropes and cords have gained significant interest in recent years as a result of the need for lighter, stronger, and easier-to-handle rope structures than those made from metallic wires for heavy-duty applications such as civil and ocean engineering. In the context of product development, building a prototype rope and testing it to determine its performance and then building another rope in an attempt to improve that performance can be very expensive. In the past, this method was affordable with small conventional ropes. When very large ropes made of polyester or high-modulus aramids are to be developed, conventional methods will be too expensive and too time consuming. Alternatively, computer modeling of the rope mechanical behavior as a function of construction, fiber type, and surrounding conditions can provide a great assistance to design engineers [15–17].

One of the key design parameters of ropes is the rope construction. Ropes can take many different constructions that serve different applications and loading demands [15]. Examples of these constructions are shown in Fig. 9.5B and C. The rope construction is commonly defined by the number of strands involved and the structures of different rope layers. In case of wire ropes and some aramid ropes, the seven-strand

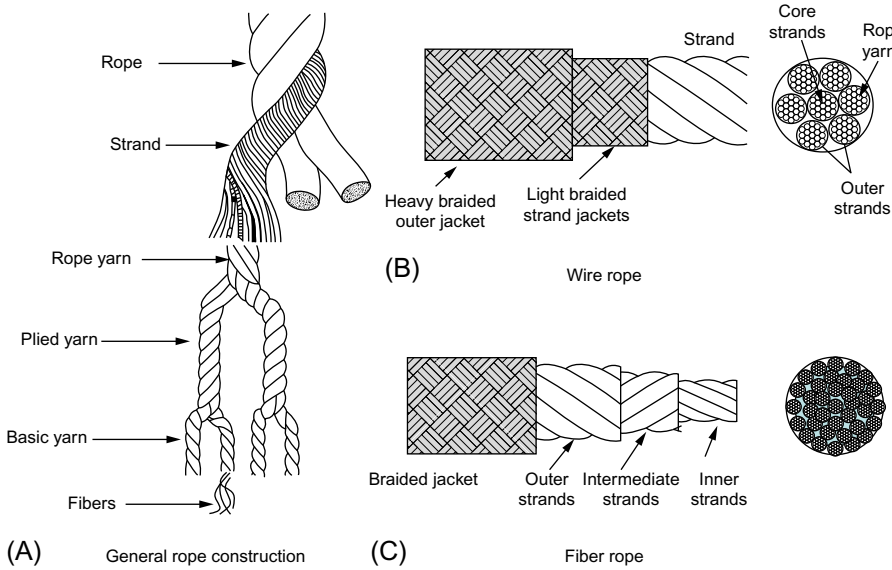


Fig. 9.5 Rope constructions [15–17].

form shown in Fig. 9.5B is commonly used. The rope typically consists of a heavy-braided outer jacket, a light-braided strand jacket, and the rope strands. More strand layers of up to 18 strands can also be used for this type of ropes. When larger ropes are required, up to 36 strand construction can be formed as shown in Fig. 9.5C. In this case, the rope strands are typically smaller in size [15]. A compact construction of this type of ropes can be achieved by using the same lay length and direction for all strands. A torque-free rope of this type can be achieved when the direction of lay of the outer strand layer opposes to that of the two inner layers (see Fig. 9.5C). A torque-free rope means that the rope does not tend to rotate when tension is applied [15]. However, this form of rope is not tolerant to torque, and a small amount of rotation can upset the balance of loads between inner and outer strand layers. Braiding is a common approach in constructing fiber ropes as it typically results in torque-free ropes. But again, they may not be torque tolerant, because applied rotation will transfer tension to only half of the strands [15]. However, they are not as easily affected by torque as the aforementioned 36-strand rope. Other construction forms include the 12-strand braided rope, which is widely accepted in conventional marine applications and the 8-strand rope (sometimes called plaited rope), which is less compact.

9.3.3 Fancy yarns

Fancy yarns, also called novelty or effect yarns, represent another category of yarns in which deliberate irregularities, discontinuities, and color variations are introduced into the yarn structure with the primary intention being the production of enhanced aesthetic and fashionable impressions [4,7,18]. Accordingly, fancy yarns are not necessarily intended for function-focus fibrous products. Many fancy yarns are produced using conventional staple-fiber spinning systems equipped with special accessories. Others are produced using special spinning preparation in which blends of various fiber colors or fiber types forming fancy slivers are used. Texturized yarns made exclusively from continuous filaments can also be considered as a form of fancy yarns.

The development of fancy yarns represents a model example of how a market can be dynamically stimulated using creative ideas that can attract consumers and draw attentions to the products at minimum added costs. Indeed, most fancy yarns merely represent random effects introduced to the traditional yarns using simple accessories mounted on conventional spinning machinery such as ring spinning or rotor spinning [7]. The manufacturing cost that may be added as a result of using these accessories is largely counterbalanced by many other factors that can indeed result in a net cost reduction. For example, fancy yarns being a result of induced irregularities and discontinuities require quality constraints and testing procedures that are much less than those implemented for traditional yarns. In addition, the possibility of using a wide range of fibers including low quality fibers and a variety of fiber wastes also adds to the overall reduction in manufacturing cost [1].

In general, fancy yarns may be divided into two major categories [4,7,18]: monofancy yarns and compound fancy yarns. The former is made from a single staple-fiber strand or multifilament yarn in which irregularities are introduced during the conversion from fibers to yarns; the latter consist of two or more fiber strands used

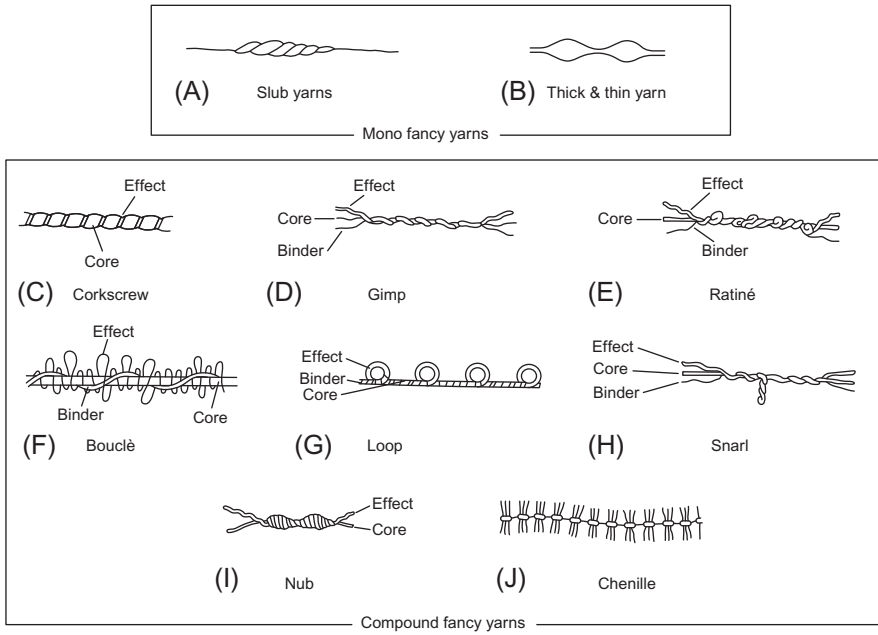


Fig. 9.6 Examples of fancy yarns [4,7,18].

to provide desired combined effects. Fig. 9.6A and B represents two examples of the first type of fancy yarns, namely, slub yarns and thick and thin yarns. Slub yarn is basically a spun yarn (ring- or rotor-spun yarn) in which thickness variations are deliberately induced via variation in yarn twist combined with a control of fiber feed so that thick areas will exhibit lower twist than thin areas. Key structural parameters associated with slub yarns include the following: slub size with respect to yarn diameter, slub length, and slub spacing or frequency. Typically, slubs are randomly and irregularly spaced along the yarn axis. A thick and thin yarn is typically a multifilament yarn in which diameter variations are deliberately induced via variation in the filament flow rate through the spinneret during extrusion. This type of yarns provides a unique surface texture to the fabric made from the yarns similar to that of linen fabrics.

Compound fancy yarns can be found in unlimited number of varieties and textures. The idea of a compound fancy yarn is to combine two or three strands together so that one of them acts as the fancy or effect strand, another acts as the yarn core, and perhaps the third one acts as a binder to secure the effect strand to the core strand. The binder strand is usually small and is often not readily visible. The differences in the appearance of the various yarns are largely dependent on the extent of prominence of the effect strand. This is typically controlled by a number of structural factors including the following: the size of the effect strand, the configuration assumed by the effect strand (wavy, looped, snarled, etc.), and the core-effect arrangement used [7,18].

The compound fancy yarns shown in Fig. 9.6C–J are listed in the order of their prominence if they are visualized side by side in a piece of fabric. These yarns can be produced using a wide range of accessories attached to commercial spinning machines.

In the context of design, it is important to point out that in addition to the deliberate irregularities induced in fancy yarns, fiber strands of different physical characteristics can also be used to make fancy yarns [4,7]. For example, the corkscrew yarn shown in Fig. 9.6C typically has a fine strand spiraling around a soft and bulky strand. When this situation is reversed (i.e., a soft and bulky strand spiraling around a fine strand), the yarn is commonly called a spiral fancy yarn. Both gimp and ratiné yarns (Fig. 9.6D and E) exhibit a slightly wavy appearance. In both yarns, the effect strand is twisted around the core strand, but ratiné yarns are usually larger and wavier than gimp yarns due to a larger effect strand. They both have an effect strand that lies closer to the core strand than is typical in boucle and loop [4].

Boucle, loop, and snarl yarns shown in Fig. 9.6F–H, respectively, have dramatic effect strands [4,18]. The effect strand in boucle yarns is usually the softest and bulkiest of this group and, typically, does not lie near the core strand. In loop yarns, the effect strand is usually made of long, rigid fibers that may also be lustrous, such as mohair or wool or untwisted thick filament strand. In both boucle and loop yarns, the binder strand is necessary to hold the loops in place [4]. The core strand in loop yarns is usually coarser and heavier than in boucle yarns. Boucle yarns are found in both woven and knit fabrics that are often called boucle fabrics. Loop yarns are frequently used in coating and suiting fabrics, for interior furnishings and for specialty fabrics, either knit or woven [4]. A snarl yarn uses a twist-lively strand to form the projecting snarls. The twist of the effect strand is usually in the same direction as the twist that holds the effect and core strands; the binder strand is usually twisted in the opposite direction [4]. Nub and slash yarns have the effect strand twisted around the core strand a number of times in a small area to form an enlarged bump or "nub." A binder strand may or may not be used. In a slash yarn, the enlarged area is longer and thinner than in a nub yarn [4].

Chenille yarns (Fig. 9.6J) resemble a caterpillar, hence the derivation of their name from the French word chenille, which means caterpillar [4]. The effect is composed of tufts of yarn held between plied yarns that form the core of the chenille yarn. Chenille yarns are usually made from cotton, wool, rayon, or polyester and are used in fabrics that are soft and velvety. The softness of chenille yarns makes them vulnerable to rubbing; consequently, fabrics containing them do not wear well because of a low abrasion resistance [4,18]. Chenille yarns are used as crosswise yarns in a woven fabric to create a velvet-like surface or occasionally placed in the filling to add surface effects. In woven fabrics, the yarns may be laid so that all the tufts lie on one side of the fabric or so that some tufts appear on both the face and the back [4]. These fabrics are used for many products such as dresses, draperies, and bedspreads. Chenille yarns are also used in knit fabrics for the purpose of making bulky sweater knits. It should be pointed out that some fabric is called "chenille" even though it does not contain chenille yarns. These fabrics are essentially tufted, and they are often used for bathrobes and bedspreads [4].

9.4 Idealized yarn structure

To understand the role of yarn in design applications of fibrous products, it will be important to first understand yarn structure. Research on yarn structure can be traced back to the early work by Gégauff in 1907 followed by Platt's work in the late 1940s and then the work by Hearle and coworkers in the 1950s and 1960s. These contributions focused primarily on the mechanical behavior of yarn and the structural features that influence this behavior. Engineers involved in the design of yarn should read the book titled *Structural Mechanics of Fibers, Yarns, and Fabrics* published in 1969 and coauthored by Hearle, Grosberg, and Backer [19]. This book provides an excellent review of these major contributions. Another excellent book by Zurek, titled The *Structure of Yarn*, translated from Polish to English in 1975, provided a critical dimension of yarn structure, which is the nature of variability in fiber arrangement in different fiber strands [20]. In the discussion in the succeeding text, an idealized twisted yarn model is described based on the work by Hearle et al. [19]. This model is shown in Fig. 9.7. Understanding this basic model can assist a great deal in understanding the real yarn structure and its effects on yarn and fabric performance characteristics as will be discussed later.

An idealized yarn structure is assumed to be in the form of a cylindrical body with well-known radius and composed of a series of concentric cylinders of differing radii, and each fiber follows a uniform helical path around one of the concentric cylinders, so that its distance from the yarn axis remains constant [19]. According to this structure, a fiber at the center will follow the straight line of the yarn axis, but going out from the center, the helix angle gradually increases, since the number of turns of twist

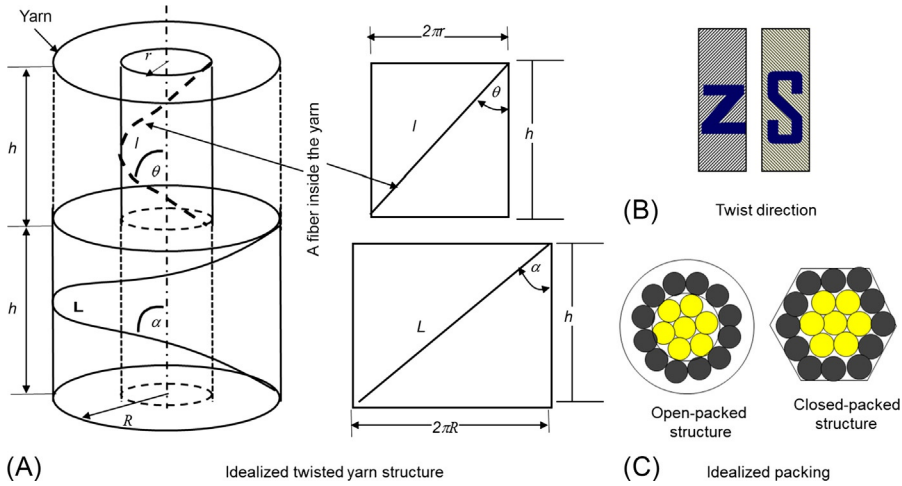


Fig. 9.7 Twist in idealized yarn structure.
Modified from J.W.S. Hearle, P. Grosberg, S. Backer, Structural Mechanics of Fibers, Yarns, and Fabrics, Wiley-Interscience, New York, 1969.

per unit length remains constant in all the layers. Under these ideal conditions, the length of one turn of twist, h, is given by $h = 1/T$, where T is the amount of twist in the yarn commonly expressed by the number of turns per unit length.

Using the opened-out surface of the ideal yarn, shown in Fig. 9.7, one can derive the following basic relationships [19]:

$$L^2 = h^2 + 4\pi^2 R^2 \tan\alpha = \frac{2\pi R}{h} = 2\pi RT \tag{9.1}$$

where R is the yarn radius, L is the length of the fiber in the yarn outer layer, and α is the surface twist angle. Using a general concentric layer of the yarn at a radius r, similar relationships for the fiber can be obtained (see Fig. 9.7):

$$\begin{aligned} l^2 &= h^2 + 4\pi^2 r^2 \\ \tan\theta &= \frac{2\pi r}{h} = 2\pi rT \end{aligned} \tag{9.2}$$

where θ is the helical angle of the fiber layer and l is the fiber length. The range of the angle θ is from zero at the center of the yarn to α at the yarn outer layer. This means that fibers at the center are straight, and the helix angle reaches a maximum α at the yarn outer layer. Thus, the yarn radius is $R = (2n-1)r_f$, where n is the nth fiber layer. In addition, all fibers in a given yarn layer have the same helix angle of twist.

One of the benefits of the idealized yarn structure stems from the possibility to define twist in terms of key yarn structural parameters such as yarn diameter and yarn bulk density. From Eq. (9.1), the twist angle is related to yarn diameter and the twist level by the following equation:

$$\tan\alpha = \frac{2\pi R}{h} = 2\pi RT = \pi DT \tag{9.3}$$

In a cylindrical yarn, the linear density of the yarn (mass/unit length) is given by

$$\frac{\text{mass}}{\text{unit length}} = \pi R^2 \rho_y = \pi \frac{D^2}{4} \rho_y \tag{9.4}$$

where ρ_y is the yarn bulk density (g/cm^3) and R is the yarn radius (cm).

Using the "tex" unit of linear density, T_t, yarn "tex" can be expressed by the following equation:

$$\frac{\text{mass}}{\text{unit length (tex)}} = T_t = \pi \frac{D^2}{4} \rho_y \times 10^5 \tag{9.5}$$

This equation gives the following expression of yarn diameter:

$$D(\text{cm}) = \left(\frac{4T_t}{10^5 \pi \rho_y} \right)^{\frac{1}{2}} \tag{9.6}$$

From Eqs. (9.3) and (9.6):

$$\tan\alpha = \pi DT = \pi T\left(\frac{4T_t}{10^5\pi\rho_y}\right)^{\frac{1}{2}} = 0.0112 \times T\left(\frac{T_t}{\rho_y}\right)^{\frac{1}{2}}$$

or

$$\tan\alpha = 0.0112(\text{Twist multiplier})\left(\frac{1}{\rho^{\frac{1}{2}}}\right) \tag{9.7}$$

The twist multiplier, TM, is a practical term used among spinner to express the level of twist in a spun yarn in terms of turns per inch and yarn count (tex), $TM = T \cdot T_t{}^{1/2}$. Following the two systems of yarn count discussed earlier, there are two systems of twist multiplier: (a) the English system, $TM = T/\sqrt{N_e}$, where T is the twist in turns per inch, and (b) the tex system, $TM = T\sqrt{tex}$, where T is expressed in turns per cm.

The idealized yarn model described earlier represents an important start to explore key structural features of yarns. However, one should consider the limitations of this model in view of understanding the nature of a real yarn structure. In this regard, many points can be made [2,3,6,19–21]:

- A real yarn, spun or continuous filament, is not perfectly circular, and most fibers do not have circular cross sections.
- The twist level is not uniform along the yarn axis due to variation in fiber properties and technological limitations that prevent a perfectly uniform twist.
- Upon twisting and due to the lateral forces imposed, circular fibers tend to exhibit elliptical cross sections.
- Fibers may take helical path in the yarn. However, this path is often distorted by the lack of full control on all fibers during spinning and the high variability in fiber length and fiber fineness.
- Fibers in the center of the yarns can be kinked or buckled.
- In a real spun yarn, many fibers will have ends projected outside the yarn body; this is known as yarn hairiness.

Despite the previous limitations, the idealized yarn structure model still represents a key guideline in understanding the basic features of spun yarns. In the following section, key design-related factors of yarn are discussed in the context of yarn structure.

9.5 Design-related aspects of yarn structure

The yarn being essentially an assembly of fibers is largely governed by three key factors that not only influence its performance during weaving or knitting but also affect the functional performance of the fabric made from it. These factors are the following [2,3]: (a) fiber compactness, (b) fiber arrangement, and (c) fiber mobility.

9.5.1 Fiber compactness

The integrity of a yarn structure is maintained partially by some form of compactness of fibers or filaments in the yarn. In case of a continuous-filament yarn, filaments adhere together, by virtue of their large number and the long interfilament contact under lateral forces imposed by the outer filaments pressing against the inner ones. This produces the highest compactness level as no air is allowed to penetrate between the filaments. When filament yarns are converted into textured yarn, a great deal of interfilament space is created leading to lower compactness. In case of spun yarns, fibers are compacted together by lateral forces imposed by the twist inserted to form the yarn. The discrete nature of the fibers provides for variable compactness with plenty of air pockets inside the yarn structure filling in the interfiber spaces.

The importance of fiber compactness stems from two important points that should be realized in the design of fibrous products. For a given fiber type, high fiber compactness is likely to result in low yarn compressibility (or low softness), high strength, low yarn flexibility, low yarn porosity, and more moisture wicking along the yarn surface than along the fibers in the yarn. On the other hand, low fiber compactness is likely to result in high yarn compressibility (or high softness), high flexibility, high porosity, and more moisture wicking along the fibers in the yarn. Between these two situations, yarns of different levels of fiber compactness can be produced to meet key fabric performance characteristics such as strength, hand, drape, moisture management, and comfort. Furthermore, fiber compactness is a key factor in determining the yarn dimensional stability; a yarn can be considered dimensionally stable if the fiber compactness is the same in the relaxed state and under low levels of stress [2].

The extent of fiber or filament compactness in a yarn structure can be expressed by two key factors: (a) the yarn bulk density (g/cm^3) or more precisely the specific volume, v_y, of yarn (cm^3/g), and (b) the volume of still air inside the yarn. One can imagine a three-dimensional yarn structure consisting of fiber material and air pockets that are created by virtue of the discontinuities of fiber flow along the yarn axis in case of spun yarns or separations between filaments in case of continuous-filament yarn or texturized yarn. Accordingly, a yarn is essentially a porous structure. Hearle et al. [19] accounted for fiber compactness in their analysis of ideal yarn model using the specific volume (cm^3/g) of yarn, derived from Eq. (9.6), and yielding the following expression:

$$v_y = \left(\frac{\pi R^2}{T_t}\right) \times 10^5 \tag{9.8}$$

This equation suggests that the density of packing of fibers in the yarn remains constant throughout the model. This idealization resulted in further theoretical analysis in which idealized fiber packing forms in the yarn were suggested [19]. These include the open-packed yarn and the hexagonally closed-packed yarn shown in Fig. 9.7C. The effect of twist on the specific volume of yarn can be realized from the following equation derived from Eq. (9.7):

$$v_y = \left(\frac{\tan^2\alpha}{4\pi T_t T^2}\right) \times 10^5 \tag{9.9}$$

The previous relationship indicates that for a given yarn count, T_t, the effect of twist on yarn specific volume is primarily a function of the variation in yarn circumference caused by twisting. Note that, from Eq. (9.3), yarn circumference is found from $\pi D = \tan\alpha/T$. Thus, according to the previous equation if the yarn has a constant diameter, as suggested by the idealized model, the specific volume will also be constant. In a real yarn, variation in yarn diameter is highly expected. An increase in yarn circumference or yarn diameter, due to twisting, will result in a quadratic increase in its specific volume or a quadratic reduction in bulk density. This situation can only hold if the increase in yarn diameter is achieved at a constant mass per unit length, T_t, or constant yarn count. Another relationship developed by Neckar [22] indicates that yarn volumetric density has approximately linear relationship with the product (twist. $\text{tex}^{1/4}$) of spun yarn.

The true specific volume of yarn will depend on the volume occupied by the fibers and by the amount of interfiber space, which is filled with air. This leads to a useful term called "packing fraction, φ" [19]:

$$\varphi = \frac{v_{fiber}}{v_{yarn}} = \frac{v_{fiber}}{v_{fiber} + v_{air}} \tag{9.10}$$

At the time the previous equations were developed, ways to measure yarn density did not exist. In recent years, measures of yarn density were made possible by Uster Technologies [23]. These measures make use of a combination of capacitive techniques to measure the yarn mass and optical techniques to measure the yarn thickness [3]. Fig. 9.8 shows values of density for some different spun yarns. Some of the interesting points that can be revealed from this figure are as follows:

- Most traditional spun yarns exhibit volumetric density ranging approximately from 0.30 to 0.6 g/cm^3. This is a wide range from a yarn-performance viewpoint as it implies a wide range of yarn bulkiness, which could have a wide range of impact on fabric performance characteristics such as compressibility, softness, porosity, and stiffness. Corresponding data for continuous-filament yarns are not available, but one can expect them to be significantly higher than those for spun yarns. Textured yarns can have a wide range of bulkiness depending on the method of texturizing used.
- Combed yarns are denser than carded yarns (see Fig. 9.8A). This is expected on the ground that the combing process results in better fiber alignment and better evenness in fiber length via the removal of short fibers and fiber hooks [2,3,6].
- Ring-spun yarns have substantially higher density than rotor-spun yarns (Fig. 9.8B). This difference is directly attributed to the structural difference between the two yarn types summarized in Table 9.3.
- Compact yarn has the highest density of all traditional spun yarns (see Fig. 9.8C). This is a direct result of the deliberate compactness of fibers in the yarn [3], making it a denser yarn (see Table 9.3).
- Yarns made for woven fabrics are denser than those made for knit fabrics (see Fig. 9.8C and D). This is a direct result of the higher twist used for the former than the latter. Yarns

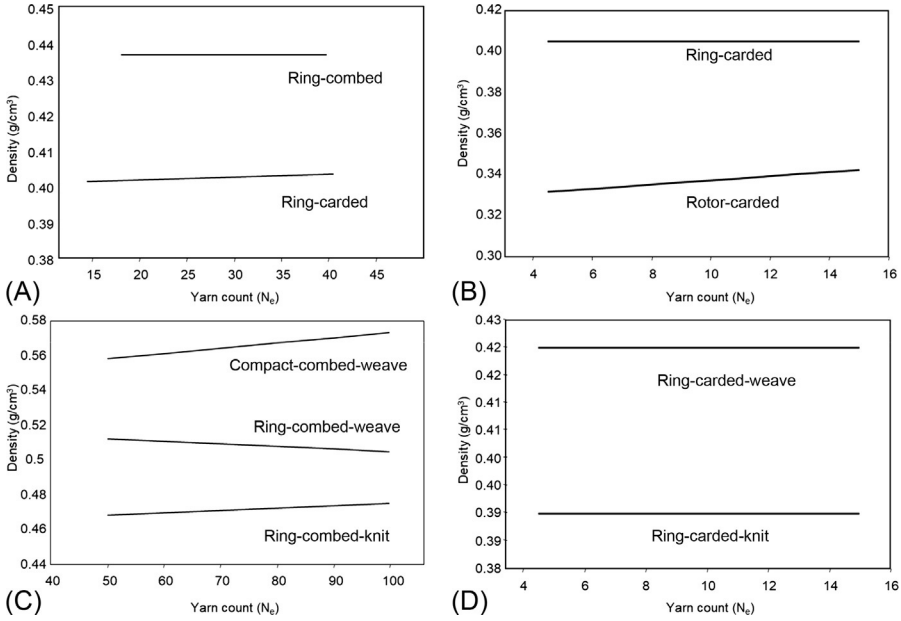


Fig. 9.8 Uster yarn density at different preparations and different spinning methods. From Uster™ Technologies Technical Data, http://www.uster.com/.

made for woven fabrics are typically stronger than those made for knit fabrics, and this requires higher twist for a given fiber type and a given set of fiber characteristics. On the other hand, yarns made for knit products are typically softer and more flexible; this requires low levels of twist.

In view of the previous discussion, the key factors influencing fiber compactness in the yarn are spinning preparation (e.g., carded vs combed), spinning method (or yarn type), and yarn twist. In addition to these factors, fiber compactness in the yarn can be altered or controlled using many fiber-related parameters for a given yarn type and yarn count. These include the following: fiber density, fiber length, fiber fineness, fiber crimp, fiber cross-sectional shape, and the number of fibers that can be accommodated in the yarn cross section [7]. For example, fine and long fibers will normally result in higher yarn density than coarse and short fibers. In addition, fibers of circular cross-sectional shape are likely to form yarns of higher bulk density than those of triangular or trilobal shapes.

9.5.2 Fiber arrangement

The way fibers are arranged in the yarn structure can have a great impact on a number of yarn and fabric performance characteristics such as yarn liveliness, yarn appearance, yarn strength, fabric dimensional stability, and fabric cover [3]. As illustrated in Fig. 9.1 and described in Tables 9.2 and 9.3, different yarn types exhibit different forms of fiber arrangement. The simplest fiber arrangement is that of a continuous-filament yarn where fibers (or continuous filaments) are typically arranged in parallel

and straight form. Deviations from this arrangement can be caused by slightly twisting the filaments or through a deliberate distortion in filament orientation as in the texturizing process. In spun yarns, fiber arrangement is quite different from the simple arrangement of continuous-filament yarns. The discrete nature of staple fibers makes it difficult to fully control the fiber flow in such a way that can produce a well-defined fiber arrangement [3,6,21]. As a result, the analysis of fiber arrangement in spun yarns typically begins with an idealized twisted yarn structure and then seeks ways to interpret or evaluate the deviation from this structure as discussed earlier.

The idealized twisted yarn structure can be useful in exploring some of the important relationships between different yarn structural parameters. However, it does not fully describe the fiber arrangement in actual spun yarn. Indeed, a yarn following this idealized arrangement will neither be practically feasible nor useful [9,20]. For example, the assumption that a yarn is composed of a series of concentric cylinders of differing radii and that each fiber follows a uniform helical path around one of the concentric cylinders implies that the outer cylinders are held firmly by some cohesive forces without fiber interference. This is not true as the fibers on the surface would be merely wrapped around and not gripped at all. In a real spun yarn, twisted fibers will still take some form of helical shape, but they can migrate from one layer of the yarn to another with some points on one fiber being on the outer layer and others being in the intermediate layers or at the center of the yarn. This creates a self-locking structure that provides the necessary integrity to the yarn. This phenomenon called "fiber migration" was the subjective of extensive research for many years [19,20]. Some yarn types may even have a greater deviation from the idealized twisted structure. For example, air-jet spun yarn exhibits no true twist with fibers in the core being largely parallel and outer fibers forming random wrapping around the core fibers. Thus, yarn structural integrity and fiber packing is largely a result of the continuity in the core fibers and the lateral pressure imposed by the wrap fibers [3].

9.5.3 Fiber mobility

A yarn structure exhibits a great deal of liveliness by virtue of fiber mobility, which is a key design aspect of yarn as it determines the dimensional stability of both the yarn and the fabric woven or knitted from it. In case of continuous-filament yarn, there is a small tendency of fiber movement in the yarn except for the tendency of filaments to split apart under buckling effects imposed by processing factors or end-use factors [5]. In case of textured yarns, bulkiness or stretch ability are both induced by some distortion in the filaments after which heat setting or self-locking of filament loops (as in air texturing) assist in providing dimensional stability to the yarn. When such conditions are partially removed (e.g., by wearing, washing, and drying), the filaments will have a greater tendency to mobilize.

In case of spun yarns, the discrete nature of staple fibers can result in many modes of fiber mobility depending on the external effects encountered [1,6]. Under minimum yarn strain, fibers will tend to settle down and cohere. If the yarn is relaxed or slack, the fibers will likely be in a bending mode; if the yarn is tensioned, the fibers will follow the path of minimum length or a straight line between fiber ends; if the yarn

is twisted, the fibers may be buckled or tend to snarl; and when a yarn end is set free, the fibers will tend to untwist. The point is that most spun yarns exhibit a great deal of fiber mobility that in one way or another can influence yarn performance during the conversion of yarn into fabrics and during the use of fabric in various applications.

Perhaps, no greater fiber mobility is observed in a yarn than that of the fiber segments or filaments near the yarn surface [19]. In an untwisted continuous-filament yarns, filaments in the outer layer will tend to snag or come loose, particularly under external rubbing conditions. For this reason, it is sometimes recommended to insert slight twist in this type of yarn to avoid snagging as mentioned earlier. In spun yarns, an inevitable phenomenon is the existence of fiber segments protruding from the yarn body. This is called "yarn hairiness," and it is measured by the number of hairs projecting from the yarn and their lengths. Typically, short hairs (<2 mm) adhered to the yarn body are acceptable as they provide a nice fuzzy feeling in apparel fabrics against the skin. This is particularly true when the protruding hairs are flexible so that they can bend easily against the skin. They may also create an opportunity to create tiny fiber pockets that can entrap air for good thermal insulation [24]. On the other hand, long hairs protruding from the yarn body can be of major adverse effect on yarn performance. During the conversion of yarns to fabrics, long hairs of different yarns will tend to entangle together creating fiber bridges that hinder a smooth flow of the yarn during processing. This phenomenon is frequently observed in the denim manufacturing process particularly in the stage of rope beaming [25]. One way to minimize or eliminate long hair is by using the singing process described in Chapter 11.

The level of hairiness in spun yarns will largely depend on a number of factors including yarn size, yarn twist, spinning preparation, and spinning method. Fig. 9.9 shows values of hairiness for different spun yarns [20]. In this case, yarn hairiness is measured by the so-called hairiness index, H, which is the length of hair per unit length of 1 cm. Thus, a hairiness index of 4 will simply mean that the accumulated length of hair of a certain yarn is 4 cm per unit length of 1 cm. Some of the interesting points that can be revealed from this figure are as follows:

- Most traditional spun yarns exhibit hairiness ranging approximately from 2.0 to 12. This is a wide range from a yarn-performance viewpoint as it can have a wide impact on fabric performance characteristics such as fabric texture, fabric hand or feel, and fabric dimensional stability.
- In general, the finer the yarn, the lower the degree of hairiness. This is generally attributed to two reasons. The first reason is a statistical one as finer yarns normally have lower number of fibers per yarn cross section leading to lower chance of creating hairiness. The second reason is that fine yarns are typically made from long fibers or combed slivers with lower percent of short fibers. Most hairiness is created by short fibers [3,6].
- In line with the previous point, combed yarns exhibit lower hairiness than carded yarns (see Fig. 9.9A).
- Ring-spun yarns have substantially higher hairiness than rotor-spun yarns (Fig. 9.9B). This is a result of the differences in the principles of the two spinning methods [3,6]. In ring spinning, the phenomenon of fiber migration forces a great deal of short fibers to be positioned near the yarn surface resulting in potential hairiness [3]. In addition, the ring-traveler system in ring spinning stimulates the hairs through the rubbing effect. In rotor spinning, the back doubling effect and the low fiber migration rate result in lower hairiness.

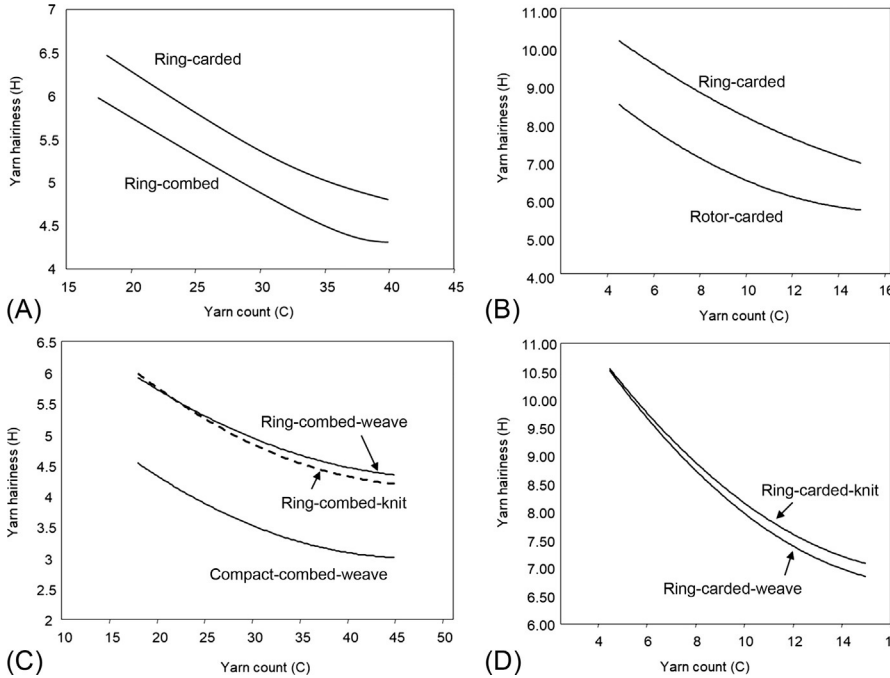


Fig. 9.9 Uster yarn hairiness at different preparations and different spinning methods. From Uster™ Technologies Technical Data, http://www.uster.com/.

- Compact yarn has the lowest hairiness level of all traditional spun yarns (see Fig. 9.9C). This is a direct result of the deliberate compactness of fibers in the yarn, making it a less hairy yarn (see Table 9.3).
- The difference between hairiness of yarns made for woven fabrics and that of yarns made for knit fabrics is not so large (Fig. 9.9C and D).

In addition to yarn hairiness, other fiber structural irregularities such as belt fibers in case of rotor-spun yarns or loose wrapping fibers in case of air-jet yarns are easily movable under the effect of rubbing against other yarns or other surfaces. This can influence the abrasion resistance and the propensity for pilling of fabrics made from these yarns [3,6].

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Textile fabrics

10

10.1 Introduction

The term fabric is not restricted to textile fabrics since many structures can be described as fabrics by virtue of their seemingly two-dimensional flat sheet structure and the large surface area-to-thickness ratio. The most generalized classification is based on whether the fabric is made from fibers or from other materials. In this regard, fabrics can be classified into two main categories: (a) fibrous fabrics such as wovens, knits, or nonwovens and (b) nonfibrous fabrics such as plastic films, rubber sheets, or metal foil. Unique structures such as paper and leather can also be classified as fibrous fabrics. However, these products are distinguished from traditional fibrous products in that their fibers are not easily identified as separate entities with clearly defined limits: rather, it is the whole aggregate that is fibrous in form. Our focus in this chapter is on common textile fabric structures and some of their advanced derivatives. In this regard, fabrics may be classified into two main categories: (1) yarn-based fabrics and (2) fiber-direct fabrics. The yarn-based fabric is made from yarns (spun or continuous filaments) through an interlacing process to produce woven fabrics or interlooping process to produce knit fabric. The fiber-direct fabric is made directly from fibers (staple fibers or continuous filaments) that are compacted or interlocked into a three-dimensional construction commonly known as "nonwoven" fabric. A third category of fabric is made through the so-called braiding process. This is typically a narrow fabric or a rope-like structure that is made by interweaving three or more strands in a diagonally overlapping pattern. A combination of these structures can also be designed to provide a wide range of performance characteristics. Details on these types of fabrics including their constructions, the technologies used for making them, and their different specifications are discussed in numerous publications [1–9].

The performance of a textile fabric in any end product stems from an integrated contribution of three key elements: fiber type, yarn type, and fabric construction. Ignoring any of these three elements in the design process of textiles could result in a failure of the functional characteristics of the end product. It should also be noted that the extent of porosity of a fabric structure will often play a significant factor in its final performance depending on the desired application. In other words, unlike other solid structures, air volume represents a vital element in the design of both traditional and technical textiles. In traditional textiles, air permeability is a key aspect in many functional characteristics such as thermal and tactile comfort. Air content also provides a great deal of fiber mobility in the fabric structure, which is required for fit and shape stability. In technical textiles, the degree of porosity can play a critical role in many applications including filtration, drainage, and acoustic insulation.

In this chapter, a brief review of common fabric constructions is presented. The purpose of this review is to provide a quick reference to the reader regarding

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the common types of fabrics available and their basic specifications. The discussion will be focused on design-related aspects of fabric constructions and textile products produced from different fabric structures.

10.2 Woven fabrics

Woven fabric is the oldest type of fabric that can be traced back to the ancient Egyptian era. It is characterized by superior durability and high dimensional stability compared with other types of fabric. In the design of textiles, different performance characteristics can be achieved using many woven fabric parameters including [7] area density, volumetric density, thickness, cover factor, and a combination of different yarns and fiber types. Most woven fabrics consist of two sets of yarns that are interlaced at right angles to each other. Yarns running along the length of the fabric are known as warp ends, while those running across the fabric or along the width are called fillings or weft picks. The way the two sets of yarns are arranged in the woven fabric is commonly known as fabric construction. This is the most critical factor that influences fabric performance. Today's weaving machines can produce hundreds of fabric constructions that can be utilized in numerous applications. The most commonly used constructions are plain, satin, and twill weave (see Fig. 10.1). These are briefly described in the succeeding text.

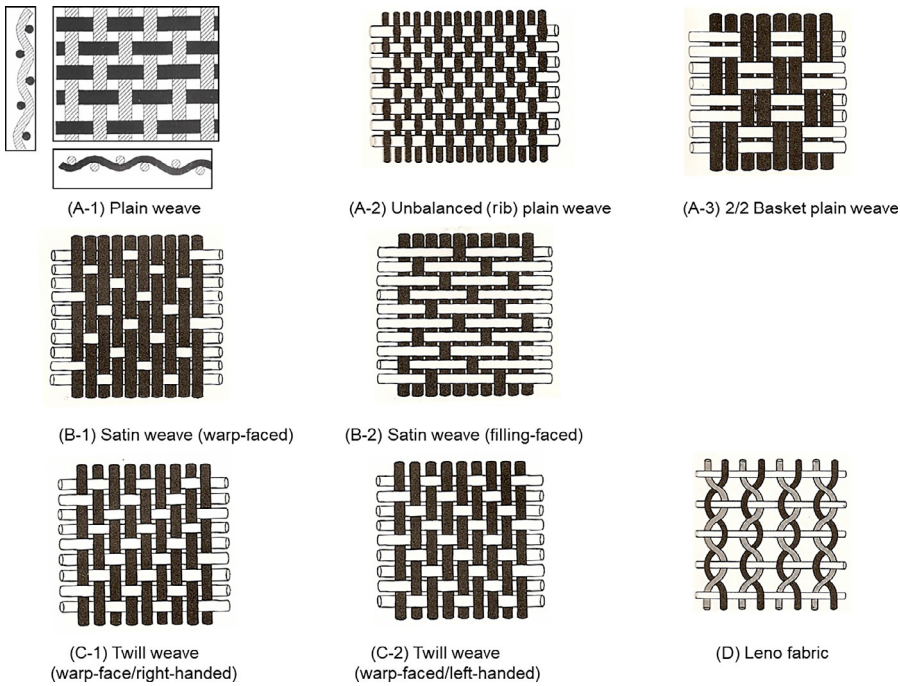


Fig. 10.1 Basic woven structures [1–6].

10.2.1 Basic weaves

The simplest woven fabric construction and the most widely used is the so-called plain weave. Indeed, one can find plain weaves used in all traditional and technical textiles. As shown in Fig. 10.1A-1, it consists of a repeat construction unit of two warp and weft yarns. It is formed by alternatively lifting and lowering one warp thread across one weft thread. The term "plain" is commonly used to indicate smooth and flat surface of the fabric. This feature is very useful for making different printing designs and for applying uniform mechanical and chemical finishing applications. When warp and weft yarns have the same yarn count and the same number per unit length, the fabric is regarded as a "balanced fabric." Typically, both the face and the back of plain-weave fabric are visually identical as a result of the consistent warp and filling interlacing. This provides ample opportunities to achieve well-controlled performance options via changes in yarn type (traditional, textured, fancy, compound, etc.), yarn count, and yarn twist. Unbalanced plain weaves are commonly called "rib fabrics" as they are characterized by the presence of ribs or ridges running crosswise on both the face and the back of the fabric (see Fig. 10.1A-2). When more than one warp yarn interlace with more than one filling yarns (2/2 or 4/4), the plain fabric is called basket weave as shown in Fig. 10.1A-3. Some fabrics may be made from two or three warp yarns floating over one filling yarns (2/1 or 3/1). These fabrics are commonly called half basket weaves. Basket weaves are commonly used in many applications including [3–6] apparel fabrics such as suits, sportswear (sailcloth), and shirts. In addition, basket weaves are used in technical textiles such as slipcovers for furniture, house awnings, and boat covers.

Satin fabric is a smooth surface fabric that is formed by floating a warp or a filling yarn over 4–12 yarns before it passes to the back of the fabric and floats under one or two yarns as shown in Fig. 10.1B-1 and B-2. Typically, the face of a satin fabric is more lustrous and smoother than the back, particularly when continuous-filament yarns are used. Satin fabrics are usually unbalanced, and they have fewer interlacing per unit area than plain-weave and twill fabrics. The smoothness and softness of the satin fabrics make them good candidates for luxurious apparels, linings, and some fancy upholstery products. They are also used in some technical textiles such as protective clothing including windproof and windbreaker jackets and coats. A derivative construction of satin fabric, commonly known as "sateen," is primarily made from spun yarns. This construction is typically a filling-faced satin weave in which the filling yarns are the yarns that float on the fabric face.

Twill fabric is a unique construction in which diagonal lines are running from selvedge to selvedge on the face of the fabric by the introduction of repeats on three or more warp and filling yarns [3–6]. When one views the fabric along the warp direction, one can see the direction of the diagonal lines on the surface of the fabric either running upward to the right, which is regarded as a "Z twill or right-hand twill" or running in the opposite direction, which is regarded as a "S twill or left-hand twill." These two constructions are shown in Fig. 10.1C-1 and C-2, respectively. By virtue of its construction, twill fabrics will obviously have longer float, fewer intersections, and more open construction than a plain-weave fabric with the same cloth attributes.

In contrast with plain fabrics, twill fabrics are rarely printed due to their ridged surface. They can also be very durable, and with the use of coarse yarns, their durability can significantly increase as in the case of denim fabrics. They are also used in other applications including [3–6] suits, sportswear, outdoor clothing, jackets and raincoats, work clothing, scarves, and neckties.

Another construction that is often used in conjunction with other weaves or independently is the so-called leno weave [3–6]. This is a special construction in which warp yarns are made to cross one another, between fillings, during leno weaving. In other words, adjoining warp ends do not remain parallel when they are interlaced with the weft but are crossed over each other. In the simplest leno, one standard end and one crossing end are passed across each other during consecutive picks as shown in Fig. 10.1D. This crossing feature can be the only feature of leno fabrics, but it can be used in combination with other weaves. The advantage of having warp yarns crossing over each other with the weft passing between them is that the warp yarns will restrict the weft movement by locking it into position. This results in an open structure (e.g., gauzes) in which virtually no thread movement or fabric distortion is observed. The same feature makes leno construction an excellent selvedge construction for binding the edge threads into position by preventing the warp threads at each side of a length of cloth from slipping out of the body of the fabric. Leno construction can also be used in the body of the fabric at points where empty dents are created to eventually slit the fabric into narrower widths. In addition to these important applications, leno fabrics can be used for special applications including [6] as sheer curtains (marquisette), mosquito netting that forms windows in tents or may be draped over a bed to provide protection from insects; as covers for the faces of beekeepers; and as sacks for laundry, fruit, and vegetable.

10.2.2 Specialty weaves

In addition to the basic weaves discussed earlier, there are other specialty woven fabrics that are constructed for various applications. These are typically more complex structures as both the geometrical texture and the design must be woven in to provide the intended performance. Examples of these constructions are crepe woven, dobby, piqué, Jacquard, pile woven, double woven, braided, and triaxial woven. These constructions are briefly reviewed in the succeeding text. More details on these weaves can be found in many literatures including the ones listed here [1–7].

Fig. 10.2 illustrates four woven constructions, namely, crepe, dobby, piqué, and Jacquard. These are mainly fashion-oriented constructions that are primarily intended for visual aesthetics. Crepe woven fabrics are characterized by random distribution of yarn floats for the purpose of producing a construction of nonsystematic repeat. This provides certain fabric textures such as crinkly, pebbly, and sandy texture. Dobby woven fabrics are characterized by geometric figures woven in a set pattern. They are often compared with the more elaborative Jacquard constructions but more limited, more efficiently woven, and obviously cheaper. Typically, the number of filling yarns in one pattern repeat is greater than that required for any of the basic weaves but less than that of the Jacquard fabrics. Piqué fabrics are characterized by rounded

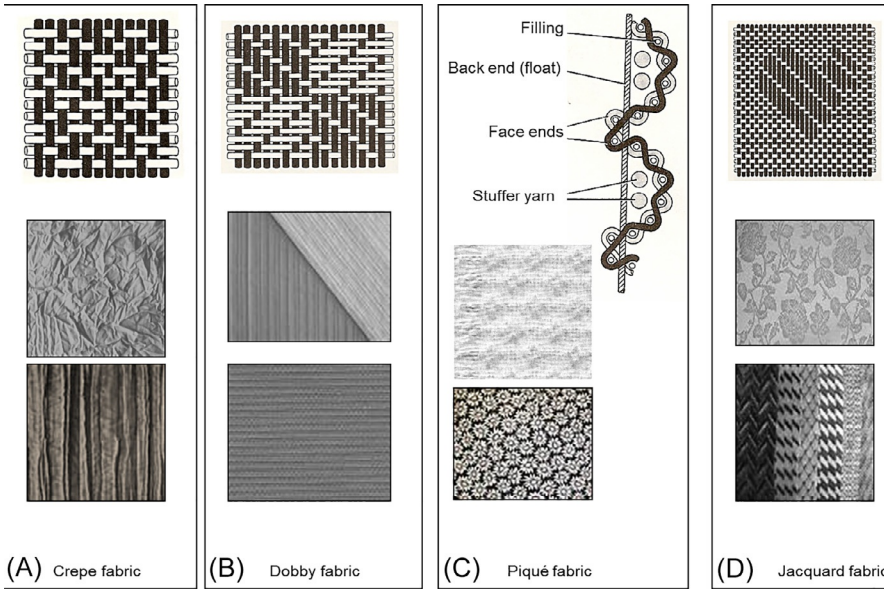


Fig. 10.2 Special woven constructions.

cords (ribs) in the filling direction with pronounced sunken lines between. Like the common quilts, they have a soft, raised-surface effect. The weave on the face of the cords is often plain woven. Jacquard fabrics are characterized by elaborate and complex woven-in patterns including some that depict paintings or complex photographs. The construction involves at least two of the basic weaves in various arrangements.

Fig. 10.3 shows the basic construction of pile woven fabrics. These are three-dimensional fabrics by virtue of their significant thickness (0.25–0.50-in. thick). This thickness is created by pile yarns that stand vertically from a woven ground reflecting the face of the pile fabric. The fabric ground typically consists of one set of filling and one set of warp yarns. To create the pile construction, another set of yarns called pile filling or pile warp yarns is interlaced into the fabric ground [5,6]. This type of fabric is used for a wide range of applications including [6] coats, jackets, gloves, and boots. It may be used as an outer fabric lining and/or interlining. The familiar terry towels are made exclusively from pile constructions. Pile fabrics can also be used in many upholstery fabrics and some bedspreads. Function-focus products made from pile fabrics include artificial turfs with piles being cut to mimic the turf natural appearance. Later in this book, more discussion on fibrous artificial turfs will be presented.

Fig. 10.4 illustrates the basic constructions of double woven fabrics. These represent multiple-layer constructions in which separate layers, each consisting of interlaced warp and filling yarns, are stitched together. One obvious reason for making double-layer fabrics is to obtain heavier and thicker constructions than single-layer constructions. From a functional viewpoint, a double-layer fabric construction allows

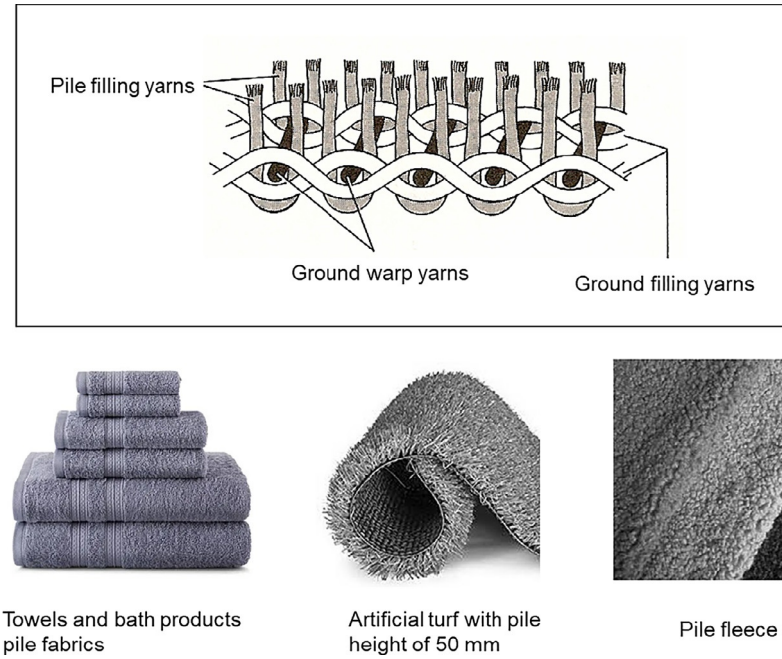


Fig. 10.3 Pile fabrics and product examples.

multiple options that may be reflected, for example, in double-faced fabrics with each face providing different visual effects or performance criteria. In addition, the fabric layers are separated by air resulting in desirable thermal insulation (e.g., blanket constructions).

Fig. 10.5 illustrates the construction of multiaxial and braided fabrics. These constructions represent another category of fabrics that are uniquely characterized by the inclination between the yarn sets forming the fabric. Triaxial fabrics are defined as cloths where three sets of threads form a multitude of equilateral triangles and two sets of warp yarn are interlaced at 60 degrees with each other and with the weft. Another type of multiaxial is the tetraaxial fabrics. In this type, four sets of yarns are inclined at 45 degrees to each other. One advantage of triaxial fabric is dimensional stability at light weight. This makes the triaxial fabric a good candidate for many function-focus applications [8,9] such as parachute gliders, sailcloths, tire fabrics, balloon fabrics, pressure receptacles, and laminated structures. They are also widely used in close fit apparels and some upholstery fabrics.

Fig. 10.5B shows the braided fabric construction. In this fabric, three or more yarns are interlaced in such a way that they cross one another in diagonal formation [6]. Most braided fabrics are narrow, and their products are those of limited widths. These include garment trims, shoelaces, and belts. Braided constructions are also used in many fiber-reinforced composite products.

A combination of braid and triaxial construction can also be made to meet some unique functional performance. For example, a US patent was presented in which a

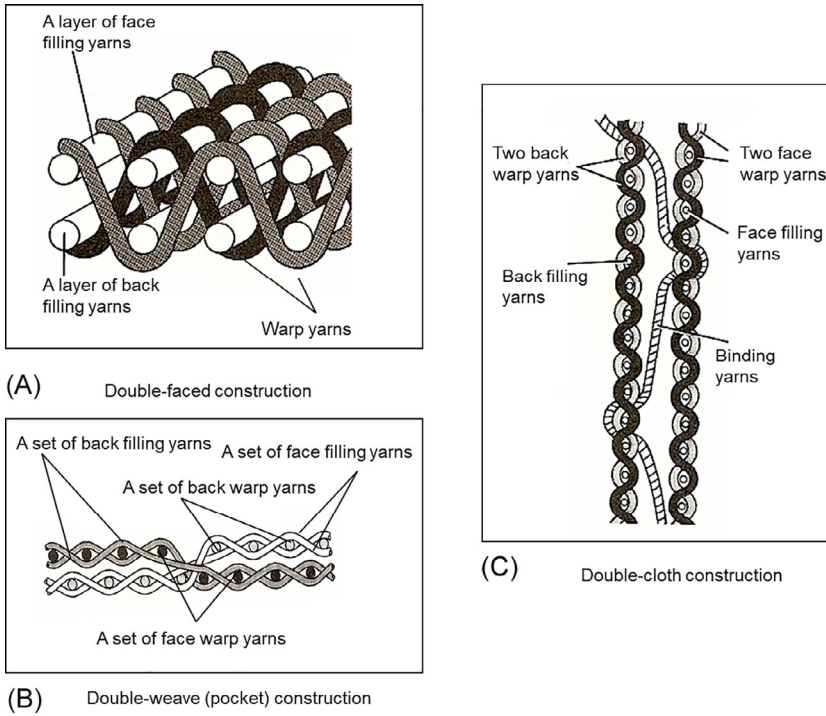


Fig. 10.4 Constructions of double woven fabrics [4–6].

novel prosthesis for use in repairing or replacing soft tissue was disclosed [9], which comprises a triaxially braided fabric element having interwoven first, second, and third sets of yarns, with the yarns of the second and third sets being oriented at substantially the same acute braiding angle with respect to the yarns of the first set. This patent claims that an elongated ligament prosthesis exhibiting the desired properties of high strength and high elasticity may be prepared by selecting high elasticity fibers for the first set, orienting first set of fibers in the longitudinal direction of the prosthesis and selecting fibers having high yield strength and high Young's modulus for the second and third sets. The patent also claims that a tubular prosthesis in which high elasticity fibers are oriented in the longitudinal direction is highly suitable for use as a vascular prosthesis and that a prosthesis of the invention may also be manufactured in the form of a prosthetic heart valve leaflet.

10.2.3 Basic specifications of woven fabrics

Woven fabrics are characterized by many parameters that collectively reflect their performance criteria. These parameters are as follows [5–7]:

- Fabric count
- Fabric width

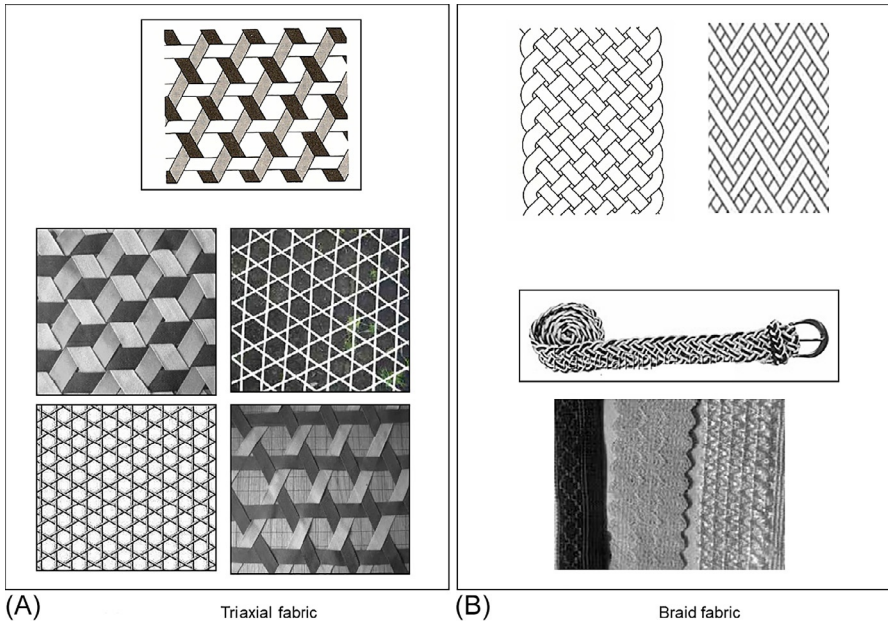


Fig. 10.5 Triaxial and braided fabrics and product examples [4–6].

- Fabric thickness
- Fabric weight or area density
- Fabric crimp
- Fabric cover factor

Fabric count is the number of threads per unit length in the warp and filling directions (warp per inch, wpi, and filling per inch, fpi) (see Fig. 10.6). These two parameters can be described independently or in a collective fashion (e.g., wpi × fpi or wpi + fpi). Standard values of fabric count are typically described for fabric off the loom or in the greige state. Obviously, the fabric width may change during dyeing and finishing, and as a result, its count may also be altered. Typical values of fabric count may range from 80 × 80 to 150 × 150. The significance of fabric count is that it reflects the tightness or the looseness of the fabric. A tight or close fabric will require finer yarns or lower number of interlacings per unit area than a loose fabric. This point is important from a design viewpoint as it indicates two independent options to develop a tight or loose fabric, namely, yarn count and number of interlacings. As indicated earlier, a balanced woven fabric is defined as the fabric that exhibits equal number of warp yarns and filling yarns per inch and contains yarns of equal size and character.

Fabric width is another characteristic that must be prespecified prior to forming any woven fabric. With the current weaving technology, woven fabrics can be made in a very wide range of width (e.g., 36–160 in.), but most fabrics are made in the range from 36 to 60 in. This range does not cover the specialty narrow fabric, which is

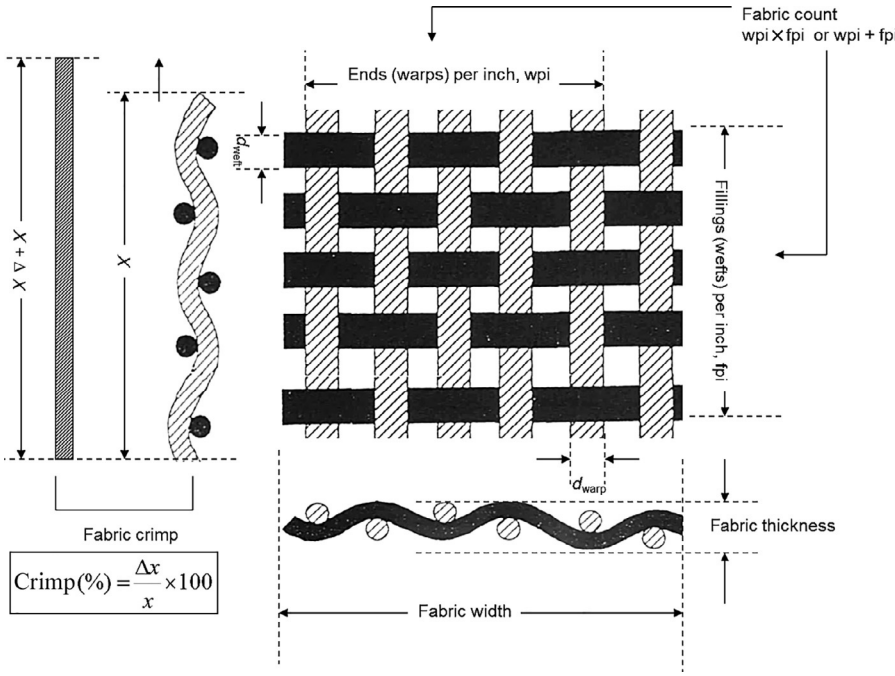


Fig. 10.6 Woven fabric basic specifications [3–7].

typically up to 12-in. wide (e.g., ribbons, elastics, zipper tapes, labels, carpet-edge tapes, and automobile safety belts). Again, the width of the fabric is likely to change upon release from the loom and under the effects of upstream chemical and mechanical finishing.

Fabric thickness is a unique characteristic of woven fabrics as it adds a critical dimension in many applications. However, it is a difficult parameter to measure. On one hand, it is not a stable parameter as it is largely sensitive to the extent of distortion in the yarn during the weaving and finishing processes. On the other hand, even under ideal conditions, the thickness should be measured under a predetermined pressure with the higher the pressure exerted on the fabric the smaller the thickness [5–7]. To make matters additionally complex, the size of the presser feet and the time elapsed before a reading is taken will also influence the accuracy of the thickness measure. These factors make it important to provide precise description of the method of testing and the testing parameters used.

Fabric weight is a key parameter in the traditional woven fabric market with heavy weights being typically assigned for bottoms such as pants, slacks, and skirts and light weights for tops such as shirts, blouses, and dresses. Commonly, fabric weight is expressed in ounces per square yard or grams per square meter. Fabrics of weights as small as 1 or less ounces per square yards are considered to be very light. A typical light fabric will have a weight, or area density, ranging from 2 to 3 oz/yd^2. Heavy fabrics typically exhibit weights of 5–7 oz/yd^2. From a design viewpoint, fabric

weight can be altered or controlled using four basic options: fiber type, yarn count, fabric count, and fabric construction. In addition, it can be altered using mechanical and chemical treatments of fabrics after weaving [6,7].

Fabric crimp is a direct result of yarn waviness in the fabric, which is caused by the yarns being forced to bend around each other during weaving. As shown in Fig. 10.6, crimp is determined by the relation of length of yarn in cloth to the length of the cloth in the warp or the filling direction. As a result, it is measured by the ratio between the length of the fabric sample and the corresponding length of yarn when it has been straightened after being removed from the cloth. Again, crimp being a mode of deformation can be difficult to measure particularly as one straighten the yarn unraveled from the fabric to measure the yarn length.

Cover factor is a measure of the area of the fabric occupied by one set of yarns, warp, or filling. As a result, there are two cover factors for each woven fabric: warp cover factor and weft cover factor. The total fabric cover factor, commonly known as the cloth cover factor, is determined by the sum of the warp and the weft cover factor, corrected by subtracting the overlap cover or the product of warp and weft cover factor. In practice, the cover factor may be calculated using the classic Peirce formula [7] in which the number of threads per inch is divided by the square root of the cotton yarn count. Alternatively, it may be calculated by multiplying the threads per centimeter by the square root of the linear density of the yarn and tex and dividing by 10. The latter typically reveals values that are different from those of the former by $<5\%$. Typical values of cover factor may range from about 12 to approximately 16 in each direction. However, cover factors of 16 or higher may result in fabric jam particularly with plain-weave constructions. Some fabrics may have even greater cover factors (e.g., duck and canvas), which requires special weaving. From a design viewpoint, cover factor can be adjusted using basic parameters such as yarn count, yarn spacing or threads per unit length, and fabric construction.

10.3 Knit fabrics

Knit fabrics are another type of yarn-based fabrics that found significant appeal in the apparel market. Today, one can find knits in numerous apparels such as sweaters, hosiery, T-shirts, golf shirts, sweat and exercise suits, lingerie, infant and children wear, swimming suits, gloves, and figure-shaping undergarments. The popularity of knit fabrics in apparel products stems from many attractive features including [6,10] the freedom of body movement in form-fitting garments, ease of care, resilience, soft draping quality, and warmth in still air environments. Knits are also used in interior furnishing and at smaller quantities in upholstery and carpets. In technical textile products, knits have exhibited wide acceptance particularly in medical applications including [6,8,10,11] splints; antithrombosis stockings; bandages; ointment pads; flat and tubular dressings; dialysis filters; incontinence pads and underwear; hospital cellular blankets and stretch terry sheets; Band-Aid fabrics; hospital privacy curtains; nets for handling burn victims; fabric for artificial heart valves; and nets for blood filtration, abdominal surgery, and reconstructions. Other function-focus

products utilizing knit fabrics include [8,10,11] scouring pads (metallic) and fully fashioned nose cones for supersonic aircrafts.

The knit structure is basically produced by employing a continuous yarn or set of yarns to form a series of interlocking loops. The two basic types of knits are shown in Fig. 10.7. These are weft-knit and warp-knit fabric [6,10,11]. The use of warp and weft is largely analogous to the same terms used in woven structures with weft being along the fabric width and warp being along the fabric length. Specifically, weft-knit fabric is characterized by a construction in which the intermeshing yarn traverses the fabric crosswise. Warp-knit fabric, on the other hand, is characterized by a construction in which each warp yarn is aligned along the fabric length or the intermeshing yarn traverses the fabric lengthwise [6]. Examples of weft-knit constructions include plain single jersey, rib, purl, and double knits (rib and interlock). Warp-knit structures include tricots and raschels. Weft knits are commonly produced in tubular form, and warp knits are mostly made in flat form.

In the following two sections, some of the features of weft and warp knits will be discussed. To follow this discussion, it is important that the reader be familiar with some of the basic knitting terminologies that will be used in these sections. Descriptions of these terminologies are listed in Table 10.1.

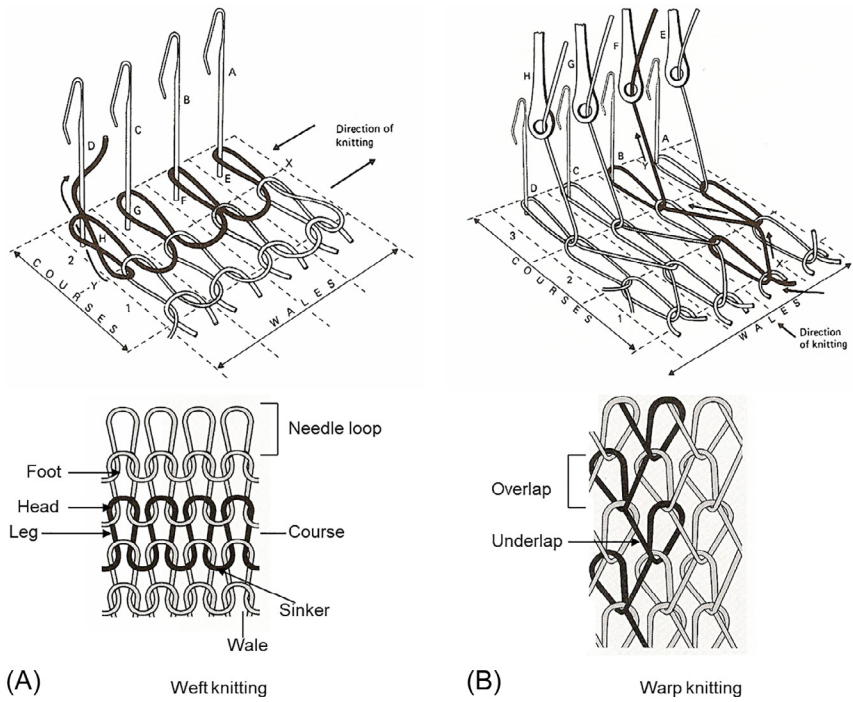


Fig. 10.7 Basic knit structures [6,10,11].

Table 10.1 Basic terms used in knitting [10–15].

Term	Description
Course	A row of loops across the width of the fabric. Courses determine the length of the fabric and are measured as courses per inch or per centimeter (see Fig. 10.7)
Wale	A column of loops along the length of the fabric. Wales determine the width of the fabric and are measured as wales per inch or per centimeter (see Fig. 10.7)
Loop	The basic unit of knit fabric
Weft-knit loop	This is commonly called "needle loop." It has a head and two legs. It also has a foot that meshes with the head of the needle loop in the course below it. The feet are usually open in weft knits; the yarn does not cross over itself. The section of yarn connecting two adjacent needle loops is called the sinker (see Fig. 10.7A)
Warp-knit loop	This is referred to as "an overlap" due to the type of motion taking place to form it. The length of yarn between overlaps, or the connection between stitches in consecutive courses, is called an "underlap." The feet of the overlaps may be open or closed, depending on whether the yarn forming the underlaps continues in the same or opposite direction from that followed during formation of the overlap (see Fig. 10.7B)
Stitch	Each loop in a knit fabric is a stitch. Knit constructions are commonly characterized by the stitch type. These include knit stitch, purl stitch, float stitch, and tuck stitch
Stitch density	The number of stitches per unit area of a knitted fabric (loops per inch^2 or per cm^2). It determines the area of the fabric
Stitch length	The length of yarn in a knitted loop. It is the dominating factor for all knitted structures. In weft knitting, it is usually determined as the average length of yarn per needle, while in warp knitting, it is normally determined as the average length of yarn per course
Cut or gauge	The number of knitting needles per unit length, along a needle bed or needle bar, of the knitting machine. It indicates the openness or closeness of the intermeshing loops. The greater the number of needles in the specified length, the higher the cut or gauge number, and therefore, the closer together the loops are to each other. As the cut or gauge is increased, finer-size yarn is used

10.3.1 Weft knits

Weft knitting is the most common type of knitting and the one that enjoys the largest market share of traditional fibrous products. Weft knitting machines are versatile, require relatively low total capital costs, and offer potentials for many economical features such as small floor space, quick pattern and machine changing, short production runs, and low stock-holding requirements of yarn and fabric.

The wide variety of weft-knit structures provides a wide range of fabric appearance and performance characteristics. Fig. 10.8 shows examples of weft-knit structures.

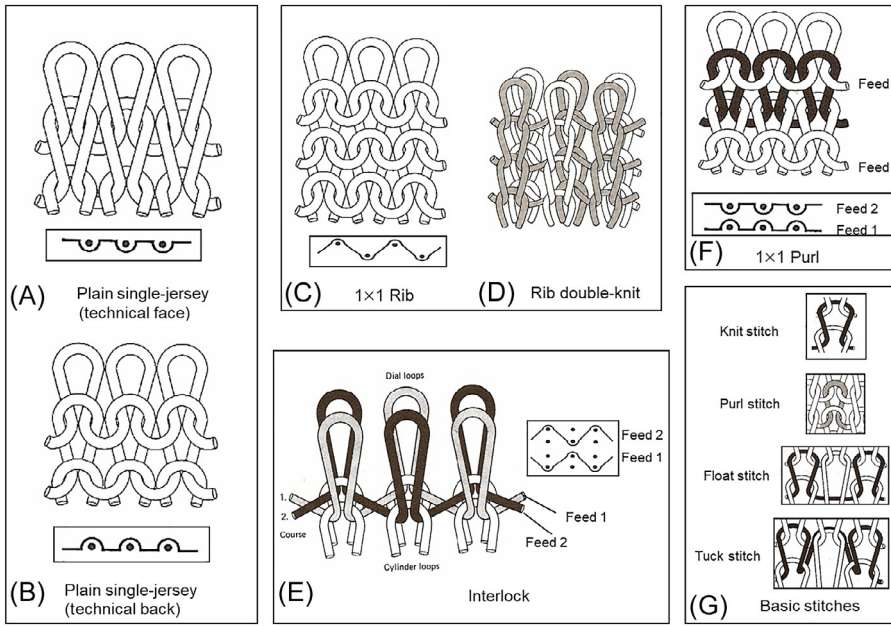


Fig. 10.8 Weft-knit structures [12–15].

The four primary base weft-knitted structures are plain, rib, interlock, and purl. As explained by David Spencer in his excellent book on knitting technology [10], each is composed of a different combination of face and reverse meshed stitches, knitted on a particular arrangement of needle beds. Each primary structure may exist alone, in a modified form with stitches other than normal cleared loops, or in combination with another primary structure in a garment-length sequence. The basic stitches that result in this diversity are knit stitch, purl stitch, float stitch, and tuck stitch (see Fig. 10.8G).

Plain knit, shown in Fig. 10.8A and B, is the simplest and most economical weft-knitted structure to produce. It is typically produced by the needles knitting as a single set, drawing the loops away from the technical back and toward the technical face side of the fabric [10]. As a result, it is characterized by a difference in appearance between the face and the back, with the face reflecting V-shapes and the back reflecting arc shape. Plain knit is the base structure of ladies' hosiery, fully fashioned knitwear, and single-jersey fabrics. It has a number of important features: typically thicker and warmer than plain woven fabrics made from the same yarn, high covering power, moderate extensibility lengthwise (10%–20%) and high extensibility widthwise (30%–50%), curling tendency, and a potential recovery of up to 40% in width after stretching.

The dominant plain knit is the so-called "single-jersey fabric" produced on circular machines whose latch needle cylinder and sinker ring revolve through the stationary knitting cam systems that, together with their yarn feeders, are situated at regular intervals around the circumference of the cylinder. The yarn is supplied from cones

mounted on a creel through tension guides, stop motions, and guide eyes down to the yarn feeder guides. The fabric, in tubular form, is drawn downward from inside the needle cylinder by tension rollers and is wound onto the fabric-batching roller of the winding-down frame. Jersey fabric is used extensively in hosiery, the foot section of socks, cotton underwear, golf and T-shirts, and sweater bodies [6].

Single-jersey knitting machines are typically simpler and more economical than rib machine [10,11]. They can also have more feeders, higher running speeds, and wider range of yarn counts. The most popular diameter is 26 in. (66 cm) giving an approximate finished fabric width of 60–70 in. (152–178 cm). According to Spencer [10], an approximately suitable count may be obtained using the formula $N_{eB} = G^2/18$ or $N_{eK} = G^2/15$, where N_{eB} = cotton spun count, N_{eK} = worsted spun count, and G = gauge in needle per inch. For fine gauges, a heavier and stronger count may be necessary.

The second type of weft knits is the 1×1 rib single knit (Fig. 10.8C). In this structure, both back and face loops (knit and purl stitches) occur along the course, but all the loops contained within any single wale are of the same sort, that is, back or face loops. In the simplest rib fabric, a $1 \times$ l, the knit and purl stitches alternate every other stitch. In other rib single knits, several knit stitches may occur in any course followed by one or more purl stitches. The rib knit is named by the number of knit and purl stitches; for example, a fabric composed of two knit stitches followed by three purl stitches is a 2×3 knit [10,11].

A 1×1 rib appears the same on both sides, with each like the face of plain knit. It has a very high widthwise elongation (50%–100%) but a moderate lengthwise elongation. It has no curling tendency as a result of the fact that it is balanced by alternate wales of face loops on each side; it therefore lies flat without curl when cut [10,11]. It is a more expensive fabric to produce than plain and is a heavier structure; the rib machine also requires finer yarn than a similar gauge plain machine. Rib cannot be unraveled from the end knitted first because the sinker loops are securely anchored by the cross meshing between face and reverse loop wales. This characteristic, together with its elasticity, makes rib particularly suitable for the extremities of articles such as tops of socks, cuffs of sleeves, waist bands, collars, men's outerwear, and underwear. Rib structures are elastic, form fitting, and retain warmth better than plain structures [6,10,11]. In circular rib machines (gauge range from 5 to 20 npi), an approximately suitable count may be obtained using the equation $N_{eB} = G^2/8.4$, where N_{eB} is the cotton count and G is the gauge in npi. For underwear fabric, a popular gauge is E 14 with a count 1/30s.

A less popular rib knit is the rib double knit produced using two staggered layers of loops (Fig. 10.8D). This arrangement is most easily seen when a rib double knit is viewed from a cut crosswise edge [10]. Even though there is considerable diversity in the structures and appearances of rib double knits, they share the characteristics of not running and being rather stiff structures with low elongation. They tend to bag, snag and shrink and have high air permeability.

The third primary weft-knit structure is the interlock (Fig. 10.8E). This was originally derived from rib but requires a special arrangement of needles knitting back to back in an alternate sequence of two sets, so that the two courses of loops show wales

of face loops on each side of the fabric exactly in line with each other, thus hiding the appearance of the reverse loops [10,11]. Interlock has the technical face of plain fabric on both sides, but its smooth surface cannot be stretched out to reveal the reverse meshed loop wales because the wales on each side are exactly opposite to each other and are locked together. Interlock elongates by about 30%–40% in the crosswise direction, so that a 30-in. (76 cm) diameter machine will produce a tube of 94-in. (204 m) open width, which finishes at 60–66 in. (1.5–1.7 m) wide. It is a balanced, smooth, stable structure that lies flat without curl. Like 1×1 rib, it will not unravel from the end knitted first, but it is thicker, heavier, and narrower than the rib of equivalent gauge and requires a finer, better, more expensive yarn. When compared with rib double knits, interlock knit tend to have higher gauges: as fine as 40 are possible in interlock double knits, compared with 28 for rib double knits. Interlock double knits have better drape and are softer, lighter, and thinner. They are used for a wide range of products including underwear, shirts, suits, trouser suits, sportswear, and dresses.

The fourth primary weft knit is the purl knit (Fig. 10.8F). This is the only structure having certain wales containing both face and reverse meshed loops [6,10,11]. This is achieved with double-ended latch needles or by rib loop transfer from one bed to the other, combined with needle bed racking. A 1×1 purl knit exhibits same appearance on both sides (like back of plain). It has very high extensibility both lengthwise and widthwise and no curling tendency. It is commonly used for children clothing and for thick and heavy underwear.

It is important to point out that each of the earlier structures requires specialized machine or machine arrangement. Thus, the diversity in weft-knit structures comes at a price [10,11]. For example, single-jersey machines can only produce one type of base structure. On the positive side, some machines may produce different structures provided that some rearrangements are made. For example, rib machines, particularly of the garment-making type, can produce sequences of plain knitting by using only one bed of needles. Interlock machines can sometimes be changed to rib knitting. Purl machines are capable of producing rib or plain knitting sequences by retaining certain needle arrangements during the production of a garment or other knitted article.

One of the recent developments in knitting technology is the "spin-knit" system introduced by Mayer & Cie company in 2011 (http://www.knittingviews.com/spin-knit-technology-by-mayer-cie/). This system knits fabrics straight from roving strands, which are the strands fed to the ring-spinning machines to make spun yarns. This development has great potentials in revolutionizing the spinning and knitting industry. A spin-knit machine combines the spinning and the circular knitting processes where single jersey is manufactured not from yarn but directly from spinning mill rovings. This eliminates two key processes between spinning and knitting: the spinning and the winding process. As indicated in Chapter 6, one of the key aspects of sustainability is shortening the manufacturing process to reduce energy and eliminate waste. The spin-knit system aims at achieving these goals by eliminating the high-energy ring-spinning process, the need for cleaning of spinning waste, and the winding process of yarn bobbins into yarn cones of larger sizes. Although the ultimate benefits of this new technology with respect to fabric quality are still under

investigation, it certainly reflects a creative design approach that can ultimately result in low cost, high rates of production, and hopefully good-quality end products.

10.3.2 Warp knits

Warp-knit fabric is similar to that of a woven fabric in that yarns are supplied from warp beams [10–15]. The fabric is produced, however, by intermeshing loops in the knitting elements rather than interlacing warps and wefts as in a weaving machine. Warp-knitted fabric is knitted at a constant continuous width. This is achieved by supplying each needle with a yarn (or yarns) and all needles knit at the same time, producing a complete course (row) at once. It is also possible to knit large number of narrow width fabrics within a needle bed width to be separated after finishing. In comparison with weft-knit structures, warp knits are typically run resistant and are closer, flatter, and less elastic.

Two of the most common warp-knit fabrics are tricot and raschel illustrated in Fig. 10.9. Tricot, solely composed of knit stitches, represents the largest quantity of warp knit. It is characterized by fine, vertical wales on the surface and crosswise ribs on the back. Tricot fabrics may be plain, loop raised or corded, ribbed, cropped velour, or patterned designs. It is commonly used for lingerie due to its good drapability. It is also used for underwear, nightwear, dresses, blouses, and outerwear [6]. Tricot fabric is also used in household products such as sheets and pillowcases. It is also be used for upholstery fabrics for car interiors.

Raschel knits have a lacelike, open construction, with a heavy, textured yarn held in place by a much finer yarn. Typically, columns of loops are connected by in-laid yarns traversing from column to column up the fabric as shown in Fig. 10.9. They split or come apart lengthwise when the laid-in yarn is removed. Examples of products made from raschel fabrics include coarse sacking, carpets, and fine, delicate laces.

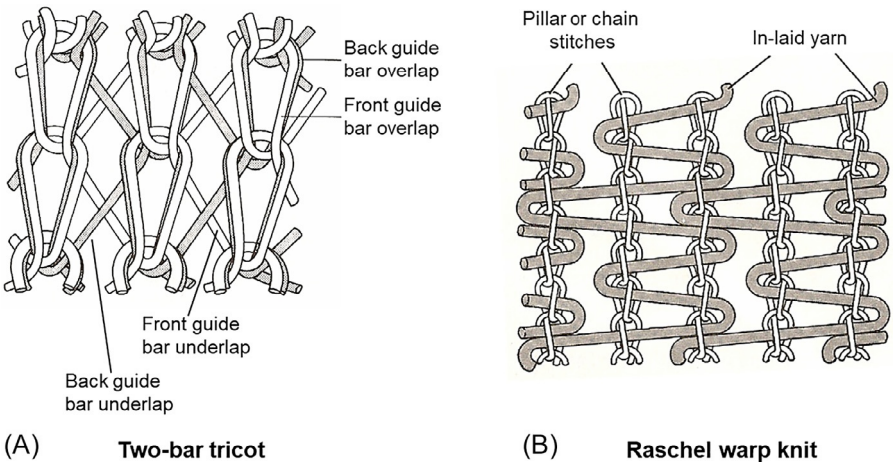


Fig. 10.9 Warp-knit structures [12–15].

10.3.3 Basic specifications of knit fabrics

Knit fabrics share woven fabrics in many common specifications such as fabric count, width, thickness, and weight or area density. In addition, specifications unique for knit structures include stitch length, stitch density, shape factor, and tightness factor (equivalent to cover factor in woven structures). Expressions and estimation approaches of knit specifications largely depend on the fabric structure under consideration [10–15]. Table 10.2 lists expressions suitable for estimating the specifications of plain single-jersey fabric.

Table 10.2 Basic formula for single-jersey knit fabrics [10–15].

Knit fabric parameter	Formula	Description
Fabric count, stitch density, and shape factor	Courses per cm $(cpc) = \frac{k_c}{l}$ Wales per cm $(wpc) = \frac{k_w}{l}$ Stitch density $= s = (cpc \times wpc) = \frac{k_s}{l^2}$ Shape factor $= \frac{cpc}{wpc} = \frac{k_c}{k_w}$	k_c, k_w, and k_s are dimensionless constants l = the stitch length
Yarn count versus machine gauge	Optimum tex $= \frac{k_{tex}}{(gauge)^2}$ or Optimum $N_e = \frac{(gauge)^2}{k_N}$	For single jersey, typical k_{tex} is 1650 For double jersey, typical k_{tex} is 1400 The gauge, G, is measured in needles per cm (npc) l = stitch length (mm)
Tightness factor	$K = \sqrt{\frac{tex}{l}} = \sqrt{\frac{T_t}{l}}$	– For single-jersey fabrics, typical K values are $1.29 \le K \le 1.64$ – For most weft-knit fabrics (including single and double jersey and a wide range of yarns): $1.0 \le K \le 2.0$
Weight or area density	Area density $= \frac{s \times l \times T_t}{100}$ g/m^2 or $\frac{k_s}{l} \times \frac{T_t}{100}$ g/m^2	s = the stitch density/cm^2 k_s = constant, its value depends upon the state of relaxation, that is, dry, wet, finished, or fully relaxed
Linear density	Linear density $= \frac{n \times l \times cpc \times T_t}{10{,}000}$ g/m or	n = the total number of needles k_c = a constant, its value depends upon the state of

Continued

Table 10.2 Continued

Knit fabric parameter	Formula	Description
Fabric width	$\frac{n \times k_c \times T_t}{10{,}000}$ g/m Fabric width $= \frac{n \times l}{k_w}$ cm or, through $n \times l = L$ (course length) Fabric width $= \frac{L}{k_w}$ cm	relaxation, that is dry, wet, finished, or fully relaxed k_w is a constant (its value depends upon the state of relaxation, that is dry, wet, finished, or fully relaxed) Fabric width depends upon course length and not upon the number of needles knitting

10.4 Nonwovens

Fiber-direct fabrics represent a unique category of fabrics in which fabrics are formed directly from fibers without the need for yarns as an intermediate component. The early term used to describe this category of fabrics, which can be traced back to the 1930s, was "nonwovens or nonwoven fabric." Today, this term remains the most commonly used name despite its obvious inaccuracy as it can imply that even knit fabrics, being nonwoven, also belong to this category. Attempts to correct this inaccuracy resulted in many alternative names such as bonded fabrics, formed fabrics, and engineered fabrics. However, each one of these terms can also be argued on the basis that woven and knit structures are uniquely bonded, surely formed, and certainly engineered. Therefore, the author of this book elected to use the term "fiber direct" due to its precise and accurate description of this important category of fabric. A "fiber direct," or FD, fabric is nonwoven, nonknitted, and nontufted. For the sake of the discussion in this section, both terms "nonwoven" and FD will be used for convenience.

The term "nonwoven" has been commonly defined by many associations as a manufactured sheet of directionally or randomly oriented fibers, bonded by means of friction, cohesion, adhesion, or combination of these, excluding paper and products that are woven, knitted, tufted, stitch bonded incorporating binding yarns or filaments, or felted by wet milling whether additionally needled or not. Fibers used for nonwoven structures may be staple or continuous filament. Fibers may also be combined with nonfibrous particles to form composite nonwoven structures. In comparison with conventional fabric forming techniques, nonwoven processes are relatively simple, productive, versatile, and economic and can be very innovative.

FD or nonwoven fabrics are made using two basic operations [16–19]: fiber web preparation (or fiber laying) and fiber bonding. In most cases, these operations are performed using a continuous process from raw material to finished product. As a result, several costly and time-consuming operations are eliminated. These

include traditional spinning preparation (e.g., drawing, combing, and roving), yarn forming, and traditional weaving preparation (e.g., winding, warping, and sizing). When fiber is the direct raw material, design options to create many products and product combinations become unlimited. This is a direct result of the possibility to use many combinations of design variables such as fiber content, fiber type, fiber blend, fiber arrangement, fiber orientation, fiber properties, web preparation, fabric thickness, bonding type, bonding density, and finishing techniques. In addition, FD fabrics can be combined with traditional woven and knitted fabrics to form many types of compound products, as will be discussed later in this chapter. These economical advantages resulted in a wide range of products most of which are of industrial nature or function-focus products.

Despite the fact that FD fabrics are made using largely continuous processes, a review of all FD fabrics or nonwovens can be a difficult task. The main reason for this difficulty is the existence of many combinations of fiber web preparation and bonding techniques. In the discussion in the succeeding text, the emphasis will be on the different types of FD or nonwoven fabrics described by web preparation and bonding technologies and common fibrous products produced from these fabrics.

FD or nonwoven fabrics may be classified by the method of laying the fiber web. In this regard, two main types of fabrics can be made [16,17]: dry-laid fabrics and wet-laid fabrics. In dry-laid fabrics, the web may be prepared mechanically (using traditional carding) or aerodynamically (using a combination of mechanical fiber opening and strong air stream). Using these methods of fiber laying, the web structure may consist of fibers that are largely oriented along the machine direction (parallel laying), largely oriented crosswise (cross laying), or largely randomly oriented. The importance of fiber orientation in the fabric web stems from the need to develop high strength in some fabric directions (anisotropic) or in all directions (isotropic) and the possibility to control fluid or air flow through the fabric structure during the use. Dry-laid fabrics are often used in interlinings, coated-fabric backings, carpet components, diaper cover stock, wipes, and sanitary napkins [6].

Wet-laid fabrics are made by processes similar to those used for paper making, which is a high-speed process. However, since fibers are relatively longer than the wood pulp used for paper making, they are dispersed into water at a higher rate of dilution (roughly 10 times greater) to prevent fiber aggregation [16–19]. In practice, a structure containing 50% textile fibers and 50% wood pulp is considered a nonwoven structure; additional increase in wood pulp content will result in a structure that is better named as fiber-reinforced paper. Wet-laid fiber webs exhibit high uniformity with weight in the range from 0.3 to 16 oz/yd^2 and thickness in the range from 0.06 to 5 mm. The dispersion of fibers results in largely random arrangement of fibers in the web. Wet-laid fabrics are often used in laminating and coating base fabrics, filters, interlining, insulation, roofing substrates, adhesive carriers, wipes, battery separators, towels, surgical gowns, diaper cover stock, and shoe components [6,16–19].

Another type of FD fabric is the so-called spun-laid or spun-bonded fabric. This is made by extruding filaments from thermoplastic polymers (mostly, polyester and polypropylene), drawing the filaments (typically using air drawing, but roller drawing is also used) and laying the filaments in the fiber web. Fiber arrangement can be controlled so that arrangement in the machine direction, some random arrangement, or

some cross-direction arrangement can be achieved [16]. This type of FD fabrics normally has high strength and high tear resistance. It is commonly used for making a wide range of products including [6,16] apparel interlining, carpet backing layers, bagging, packaging, filtration, wall coverings, and charts and maps. It is also used in function-focus applications such as geotextiles, house wrap vapor barriers, and protective apparel. The use of microdenier filaments in this type of FD fabrics provides many advantages including [16] better filament distribution, smaller pores between the fibers for better filtration, lighter weight, and softer feel.

Other derivatives of spun-bonded fabric are flash-spun fabric and melt-blown fabric. Flash-spun fabric is made from a specialized technique for producing very fine fibers without the need to make very fine spinneret holes [16]. In this case, the polymer is dissolved in a solvent and is extruded as a sheet at a suitable temperature so that when the pressure falls on leaving the extruder, the solvent boils suddenly. This blows the polymer sheet into a mass of bubbles with a large surface area and consequently with very low wall thickness. Subsequent drawing of this sheet, followed by mechanical fibrillation, results in a fiber network of very fine fibers joined together at intervals according to the method of production [16,18]. Melt-blown fabrics are also made from a process in which very fine fibers are produced at high production rates without the use of fine spinnerets. The polymer (polypropylene or polyester) is melted and extruded in the normal way but through relatively large holes. As the polymer leaves the extrusion holes, it is hit by a high-speed stream of hot air at or even above its melting point, which breaks up the flow and stretches the many filaments until they are very fine. At some point, the filaments break into fine staple fibers, which are collected into a batt on a permeable conveyor. Melt-blown fabrics can be layered with spun-bonded fabrics to form spun-bonded/melt-blown composites (called SMS fabrics).

Nonwovens being fiber-direct fabrics will rely largely on fiber-to-fiber entanglement enhanced by interfiber frictional forces to hold the fabric structure together. However, this cannot be the only way to achieve web integrity particularly in situations where thin webs consisting of small amount of fibers are to be produced. Thus, additional adhesives should be used to enhance the integrity of those structures. In this regard, a common way to classify nonwoven fabrics is by the bonding technique used to maintain the fabric integrity. There are two major categories of nonwoven fabrics: (a) mechanically bonded fabrics and (b) media-bonded fabrics. Mechanically bonded fabrics are made using familiar methods of bonding such as needle punching, hydroentanglement, and stitch bonding. Media-bonded fabrics are formed using external effects such as chemical adhesion and thermal exposure. It is useful, therefore, to discuss nonwoven structures with respect to these main types of bonding as this type of discussion reveals many insights into the design of textiles using fiber-based structures.

10.4.1 Mechanically bonded fabrics

Some fibers have a great ability to intermingle and entangle together by virtue of their surface morphology. The most familiar fiber that exhibits this unique characteristic is wool. Like human hair, the surface of wool fiber is characterized by natural scales that

provide differential interfiber friction or greater friction when fibers are rubbed against scales than when rubbed with the scales. This phenomenon resulted in the development of the so-called felt fabrics that consist of 100% wool or blends of wool and other fibers. To make felt fabrics, fibers are interlocked by mechanical compacting supported by heat, moisture, and interfiber friction [6]. The web made this way is then passed through a solution of soap or acid that causes the fabric to shrink and harden even further. Felt fabrics are known for their resiliency, sound absorption, vibration damping, shock absorption, and thermal insulation. However, felt fabrics are typically stiff and often hard to manipulate (folding or bending). Felt fabrics can be found in many end products such as some interior fabrics, hats, house slippers, clothing decoration, pads for high production machinery, high-fidelity speakers, acoustic wall covering in auditoriums and public spaces, vibration-damping components for sensitive instruments, plumbing seals, and marine gaskets.

Another type of mechanically bonded fabrics is the needled-punched or needle-felt structure. This is formed by using special needles to induce interfiber cross-linking effect in the fiber web or batt [16,17]. In this case, any fiber type of staple form can be used. Needle-punched fabrics are typically more dimensionally stable than comparable felt fabrics. In some cases, a lightweight, open-weave fabric is incorporated into the center of the web to provide additional integrity to the needle-punched fabric. End products made from needle-punched fabrics are numerous. These include [4,15] blankets and carpets (mostly acrylic or acrylic blends), outdoor carpets (mostly olefin fibers), backing in tufted carpets, supporting material in ballistic protective vests, filter media, coated-fabric backing, apparel interlinings, road underlay, and auto trunk liners.

Hydroentangled fabrics, also called spun-laced fabrics, are produced using high-pressure water streams (as high as 2200 psi) that simulate the needle action to entangle the fibers in the fiber batt. The formed web (usually air laid or wet laid, but sometimes spun bond or melt blown, etc.) is first compacted and prewetted to eliminate air pockets and then water needled. Fabrics produced using this bonding method are typically of soft handle and have good drapability [16,17]. When hydroentanglement is applied for dry-laid (carded or air-laid) or wet-laid webs, man-made fibers such as PET, nylon, acrylics, and Kevlar can be used. Blends of cotton fibers and man-made fibers are also used. Cotton being hydrophilic in nature provides an inherent bonding ability caused by a high content of hydroxyl groups, which attract water molecules. Upon evaporation of water from the fiber batt, hydroxyl groups on fiber surface link together by hydrogen bonds. Products made from hydroentangled fabrics include [4,16] wipes, draperies, quilt backings, curtains, table cloths, some apparel, surgeon gowns, disposable protective clothing, and backing fabrics for coating.

Another type of bonding that can be categorized as mechanical bonding is stitch bonding.

Stitch-bonded fabrics are made using cross-laid and air-laid batts bonded by a series of interlooped stitches running along the fabric length. Stitching can be applied using external yarns (sewing or warp-knit stitching) or by interloping the fibers in the batt. Products made from stitch-bonded fabrics cover a wide range of applications, and some of these products require special methods of stitch bonding [19]. These products include [6] interlinings for garment, shoe, and upholstery fabrics; decorative

fabrics such as textile wallcoverings and dishcloths; and backing fabrics for coating. Most of these are made using thread stitch-bonded fabrics. Products made from threadless stitch-bonded fiber webs include backing layer for coated fabrics, textile wallcoverings, decorative felts, packing materials, and insulating materials.

10.4.2 Media-bonded fabrics

Media-bonded fabrics are formed using external effects such as chemical adhesion and thermal exposure. Chemically bonded fabrics are produced using an adhesive agent (e.g., acrylic latex, styrene-butadiene latex, and vinyl acetate latex) for the complete batt or only isolated portions of the batt. Good adhesion of the fibers necessitates fiber wetting, which is achieved by the surfactants that are normally contained in the lattices and in some cases using additional surfactants [16–18]. The latex is then dried by evaporating the aqueous component, leaving the polymer particles together with any additives on and between the fibers. During evaporation, the surface tension of the water pulls the binder particles together forming a film over the fibers and a rather thicker film over the fiber intersections [16]. Finally, the fiber batt is cured by increasing the temperature to a level higher than that used for drying (120–140°C for 2–4 min). Curing results in a significant increase in the cohesive strength by forming cross-links both inside and between the polymer particles.

Thermally bonded fabrics are produced using melting as the key bonding technique [17,18]. In this regard, localized melting spots may be created for webs consisting of one type of thermoplastic fibers. Alternatively, a blend of fibers of different melting points or a blend of thermoplastic and nonthermoplastic fibers can be used. Another common method is to use a bicomponent fiber of a high melting point core polymer surrounded by a sheath of lower melting point polymer. In this case, the core of the fiber will not melt but will support the sheath in its fibrous state.

10.4.3 Nonwoven finish

In addition to web formation and bonding techniques, nonwoven structures can be treated chemically with a wide variety of finish. Numerous methods can be used to apply chemical finish to nonwoven structures depending on the raw material used and the type of bonding [16–19]. These include impregnation, printing, spraying, and coating. In Chapter 11, more details on different types of finish will be presented. For nonwovens, the finish can be applied to the bulk of material or on the surface (both sides and either side). From a design viewpoint, these applications create multiple-layer structure, with each layer performing a separate task. Chemical agents can be added to nonwoven structures to improve certain characteristics such as handle, rigidity, softness, abrasiveness, absorption, flame resistance, and antistatic properties. Specialty finishes can also be added to enhance specific performance characteristics. For example, odor control and microbial attacks can be treated using special finishes such as activated carbon, zeolites (for odor control), antimicrobials agents, and coatings for barrier properties. Other finishes are applied for slip control, adhesion

(pressure sensitive and thermoplastic), cohesion, and microspheres to increase volume or to incorporate perfumes and other potential additives.

10.4.4 Potentials for nonwovens in the apparel field

In the area of human-contact products, particularly apparel goods, FD fabrics did not have the same appeal as the traditional yarn-based fabrics for the following reasons [20]:

- The use of yarn as an intermediate component allows a great deal of structural integrity and long-term durability.
- Yarn-based fabrics enjoy relatively greater flexibility as a result of the use of self-bonding techniques such as twisting and interlacing. This is a key performance criterion particularly in relation to tactile comfort and in applications where fabrics must be manipulated (folded, bent, cut, etc.) in product assemblies.
- The use of yarn provides a great deal of surface integrity and surface conformity in applications where the fabric must come into direct contact with the human body.

Apparel products utilizing nonwoven fabrics today include interlinings, clothing and glove insulation, bra and shoulder padding, handbag components and shoe components, high-loft insulation, protective clothing, boot insulators, synthetic suede, and undercollar material. In the late 1960s, some efforts were made to market disposable dresses made entirely from nonwoven fabrics but with little success. The development of complete nonwoven apparels represents an interesting design challenge. In this regard, key performance criteria include fabric drape, fabric hand, stretchability, and bulk and surface durability particularly when washable nondisposable apparels are the target products. The development of nonwoven structures such as spun bonded, melt blown, and stitch bonded provides potentials for moving into the apparel market [6]. These potentials are enhanced by the fact that unlike woven and knit fabrics, nonwovens do not ravel; therefore, seams do not need to be surged, making it easy to incorporate shaped hemlines into the garment design. Seams within the garments also do not require finishing. However, many challenges are still ahead, and more research is needed in this critical application.

10.5 Compound fabrics

The categories of fabric discussed in the previous sections represent the basic fabric structures and some of their derivatives. Most of these fabrics exhibit light weight, fair to excellent strength, and superior flexibility compared with many nonfibrous structures. In addition, the use of different fiber types, various fiber-blend ratios, and different yarn structures provides numerous design options and unlimited expansion of the use of fibrous structures even in applications that were not conceivable few years ago. In many areas, complex and conflicting requirements may be placed, and meeting these requirements using one particular fabric structure may be impossible. In these situations, compound fabrics consisting of different fabric layers, each providing specific functions, should be the focus of the design tasks. Fortunately, basic

fabric structures can be combined in many different ways to produce compound fabrics that can serve in a wide range of traditional and function-focus applications. Common examples of compound fabrics include [6,18] quilted fabrics, tufted fabrics, flocked fabrics, coated fabrics, and laminated fabrics. These different types of compound fabrics are available commercially, and developments and investments in these exciting structures have never ceased. In the discussion in the succeeding text, a brief review of some compound fabrics is provided. It should be pointed out, however, that the best references dealing with accurate information about these specialty fabrics should be the technical information provided by their manufacturers.

10.5.1 Quilted compound fabrics

Quilted compound fabrics typically consist of a filler fibrous layer (e.g., nonwoven structure) sandwiched between two thin fabric layers. Quilting may be achieved using a sewing machine to apply mechanical stitch bonding or using an ultrasonic quilting machine to apply fusion bonding [18,19]. The latter requires the use of high percentage of thermoplastic fibers so that the high-frequency ultrasonic vibration can cause the fabric layers to fuse together at points along the surface. Design variables associated with quilted fabrics include fabric type of the face and back layers, fiber content in the filler (volume and blend ratio), stitching rate, and stitch pattern. Products made from quilted compound fabrics include cold-weather garments, upholstery fabrics, mattress pads, bedspreads, and some protective vests.

10.5.2 Tufted compound fabrics

Tufted fabrics consist of tufts or loops (cut or uncut) formed by inserting yarn into a previously prepared backing fabric (woven or nonwoven). This is a form of pile fabric in which the yarn forming the pile stands vertical from the base of the fabric [6,16,17]. To hold the pile yarn in place, a thin adhesive coat is often applied to the back of the fabric, or a secondary backing is added. Design variables associated with tufted fabrics include the gauge length (the distance between rows of stitches), stitch length, pile height, and loop condition (cut or uncut). The most commonly made product made from tufted fabric is carpet. This type of carpets is less expensive and requires lower operator skills than comparable woven carpets. Other products made from tufted fabrics include upholstery, bedspreads, and fur-like components used for hells or linings of coats and jackets.

10.5.3 Flocked compound fabrics

Flocked fabric may be considered as another derivative of pile fabric [6,16,17]. It provides a velvet-like surface using very short or pulverized fibers attached and held to a base of fabric with an adhesive. Design variables associated with flocked fabrics include fiber type, base type, the adhesive used, pile height, and pile density. Common fiber types used for flocked fabrics include rayon, nylon, polyester, olefin, and acrylic. Products made from flocked fabrics include velvet-like upholstery fabrics, draperies,

bedspreads, wallcoverings, blankets, and children's and women's clothes. They may also be used as outer fabric for stuffed toys, air filters, nonslip patch fabrics on boat decks and swimming areas, handbags, and belts.

10.5.4 Coated and laminated compound fabrics

Coated fabric is a compound fabric due to the fact that the coating layer, which is typically a continuous polymeric material, is considered as an independent layer attached to the fabric via its inherent adhesive properties [6,16,21]. The fibrous structure can be of any of the basic structures, namely, woven, knit, or nonwoven. Polymeric materials used for coating is typically function oriented, and they are used for many purposes including chemical resistance, antistain (or low surface energy), release, hydrophilicity, vapor and gas barrier, electrical conductivity, and abrasion resistance. A key design challenge of coated fabrics is the need for altering the fabric surface without affecting its overall physical and mechanical properties. Numerous products can be made from coated fabrics. These include chemical protective clothing, waterproof clothing, upholstery fabrics, wallcoverings, women's shoe uppers, floor coverings, bandages, acoustical barriers, filters, soft-sided luggage, awnings, ditch liners, and air-supported structures.

Laminated fabrics consist of two or more layers, at least one of which is a textile fabric, bonded closely together by means of an added adhesive or by the adhesive properties of one or more of the component layers [6,16]. A common type of laminated fabric is the so-called film laminate. In this type, one component is a film, or a thin, flexible sheet of polymeric material. This film is typically bonded using adhesive to a base fabric or between two fabrics. Film laminated fabrics can be used for waterproof applications such as shower curtains, tablecloths, shelf covers, and waterproof rainwear. Another type of laminated fabrics is the so-called foam laminates used primarily for insulation purposes. In this type of fabrics, a thin foam layer (e.g., polyurethane foam) is present giving small numerous air bubbles in a lofty, bulky, springy, elastic-like structure. Since foam cannot be used alone due to its weakness, the fabric layers act as a container of the foam layer. Foam laminates are used in the manufacture of spring coats and bathrobes, where a warm and lightweight fabric is needed.

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Finished fibrous assemblies

11

11.1 Introduction

Fabrics exiting the weaving or the knitting machine are commonly labeled "greige" fabrics. This term refers to unfinished woven or knitted fabric that hasn't been bleached or dyed. At the greige state, a textile fabric should exhibit most of the basic characteristics that were specified at the design phase of the fabric. However, greige fabric is typically unsuitable for making textile end products due to the following reasons:

1. The fabric may not be fully clean as a result of many impurities that were presented in the fiber assemblies leading to the fabric.
2. The fabric may suffer shade variation due to the presence of multiple colors in fibers (e.g., cottons of different reflectance or yellowness levels and blended fibers of different colors).
3. The fabric may suffer deficiencies resulting from some adverse effects of the various manufacturing operations that fibers must go through including excessive yarn and fabric defects and dimensional changes imposed by the mechanical stresses during weaving or knitting.
4. The fabric may suffer deficiencies resulting from inherent limitations in the fiber or yarn used to make the fabric including excessive projecting fibers, thick and thin places in yarn, and fabric pills.

The aforementioned problems make it necessary to apply basic fabric finish for the purpose of removing, masking, or minimizing the aforementioned effects.

In modern technology, the role of fabric finish has been significantly extended not only to play a reactive role to overcome fabric problems but also to contribute substantially to the esthetics and the functional performance of textile end products. This role makes fabric finish an essential factor in the design of textiles. The esthetic features are primarily produced by the color of fabric and the smoothness of its surface. As indicated in Chapter 5, the dyeing process provides many color and appearance options that are critical in satisfying style and appearance features of textiles. Different fibers require different types of coloring agents that are chemically compatible, which means that the dyeing chemical must be engineered in and colorfast must be carefully designed to avoid fading of color as a result of exposure to sun or upon repeated washing and drying. The process of dyeing textiles involves many options including fiber dyeing, yarn dyeing, or fabric dyeing. Furthermore, many methods of dyeing can be used including [1] piece dyeing, roller dyeing, fabric printing, screen printing, heat-transfer printing, digital printing, and garment dyeing. These represent many options that a design engineer can utilize in finding optimum solutions of design problems associated with color and surface patterns.

The functional performance of textile end products primarily stems from key design factors such as fiber type, fiber properties, yarn type, yarn properties, fabric construction, and fabric properties. Fabric finish can play a critical role in either

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enhancing the contributions of these basic factors or adding other performance-related characteristics to the end product. These include wrinkle resistance, antistatic, water repellency, flame retardation, and antibacterial. More advanced finish treatments can indeed result in a smart fabric with performance characteristics that can accommodate changing environmental conditions (e.g., thermally adapted finish and self-cleaning treatments).

In this chapter, a brief overview of some of the common finish treatments is presented. The main purpose of this overview is to emphasize design-related aspects of the finishing process that can assist engineers in reaching optimum solutions of design problems associated with traditional and technical textiles. Again, this is not a comprehensive review of the different finishing processes, and the reader should refer to references devoted to this important subject.

11.2 Yarn finish: Sizing and waxing

The weaving process applies significant mechanical stresses on the spun yarn; it stretches the yarn, possibly beyond its elastic limit, and it involves a great deal of rubbing, interyarn friction, and yarn/metal abrasion. Unfortunately, most staple-fiber yarns, as spun, cannot withstand these effects [2–4]. They exhibit strength that can easily fall below the applied stress during weaving (particularly the weak points in the yarn), they lack perfect uniformity and smoothness, they have many knots and slubs, and they may exhibit a great deal of hairiness. These defects are virtually inevitable despite the great progress in spinning technology. As a result, a protective film must be temporarily applied to the yarn to provide toughness, surface uniformity, abrasion resistance, and low hairiness (or projecting fibers from yarn surface). This is achieved using the so-called "sizing" or "slashing process." In this process, spun yarns are coated with a temporary protective film so that they can withstand the rigorous weaving process. A wide variety of film materials is typically used including [2] starch, polyvinyl alcohol, carboxymethyl cellulose, gums, glues, dextrine, acrylic film, synthetic polymers, and copolymers. For staple-fiber yarns (or spun yarns), starch and polyvinyl alcohol are the size films most often used. Synthetic polymers are commonly used for sizing filament yarns.

Upon weaving, the size material must be removed using the so-called desizing process. Therefore, it is important to know the base size used as size material must be desized using certain treatments. For example, starch can be degraded into water-soluble compounds such as enzymes, acid hydrolysis, and oxidation. Carboxymethyl cellulose (CMC) is soluble in cold water. Polyvinyl alcohol (PVA) will also dissolve in water without initial degradation. Fabrics sized with PVA are desized through saturation with water containing a wetting agent, heating, and rinsing in hot water.

During knitting, spun yarns are also subjected to mechanical stresses but not as significant as those associated with the weaving process. The most significant effect in this process is the yarn-to-metal friction during knitting. For this reason, yarns are typically treated with a paraffin wax coat in dry state to provide a smooth yarn

surface during knitting. This type of treatment must be very uniform along the yarn length. Ideally, paraffin wax should lie between the protruding fibers on the yarn surface, and it should not penetrate into the yarn core so that it does not hinder yarn's elasticity. There is a wide variety of wax material available commercially that may be different in texture, fineness, and melting point. The level of wax deposited on yarn will have a significant effect on the dynamic characteristics of yarns during knitting. In general, a reduction of up to 50% of yarn coefficient of friction can be achieved using the wax treatment. However, this requires an optimum wax content as too much paraffin can lead to undesirable film, which can result in an increase in yarn friction. The relationship between wax content and yarn coefficient of friction exhibits a minimum point below which wax content may not be enough, yielding high coefficient of friction, and above which the coefficient of friction can also increase. This relationship will also be influenced by the running speed of the yarn during knitting. A typical optimum wax content is about 0.5- to 1.0-g paraffin per kilogram of yarn. In addition, steaming or high humidity conditioning of wax yarns can result in an increased in friction coefficient. Steaming can melt the wax and causes penetration of wax into yarn body.

11.3 Fabric finish

As indicated in the introduction, prior to forming an end product, the fabric must be modified using chemical, thermal, or mechanical treatments so that desired final bulk, surface, or geometrical characteristics can be obtained. In the context of product development, these treatments (collectively called finishing) sometimes represent the most critical phase of product design as they can indeed influence many of the performance characteristics of fibrous products.

Fibrous assemblies are characterized by two basic features: (a) They are mostly polymeric based, and (b) they are flexible in nature. The first feature allows manipulation and modification of the characteristics of fiber assemblies via chemical or thermal alteration, and the second feature allows mechanical manipulation. Accordingly, finish applications are generally divided into three basic types: chemical, thermal, and mechanical. Finish treatments may also be classified into preparatory finishes and performance-enhancement finishes. Preparatory finishes commonly aim at producing a clean and impurity-free fabric so that further dyeing and finishing treatments can be applied uniformly and without interference. Examples of preparatory finishes are as follows [1, 5–7]:

- Singeing: Burning away loose projecting fibers and fuzz that are projecting from yarns or fabrics.
- Desizing: Removing the size film during fabric finishing.
- Scouring: Washing yarns or fabrics from natural dirt, waxes, and grease.
- Bleaching: Applying a whitening agent on fabric surface.
- Mercerizing: Treating cellulosic-based yarns or fabrics with caustic treatment to provide luster, water absorbance, dye yield, and fiber strength.
- Carbonizing: Treating wool material with acid for removing vegetable matter.

- Heat setting: Applying heat treatment to thermoplastic materials to provide dimensional stability.
- Tentering: Fabric drying under gripping constraints to rebalance the fabric and to reach a prespecified fabric width.
- Calendering: This is analogous to ironing the fabric under high pressure (up to 1 ton/inch^2) with the result being to flatten the fabric, making it smoother and more lustrous. It can also serve as a water squeeze when the incoming fabric is wet or to enforce resins and other finish added to the fabric prior to calendering.

Performance-enhancement finishes are commonly applied to improve some performance characteristics such as flame resistance, stain and water resistance, hand, durable press, and soil release. In the following sections, brief descriptions of many common finish treatments are presented.

11.3.1 Examples of preparatory finish

11.3.1.1 Singeing

Singeing is essentially a burning process of the free fiber ends projecting from the fabric surface using gas flame [1]. It is typically used as an initial stage of fabric finishing, particularly with fabrics made from staple-fiber yarns such as cotton. The fabric is passed at high speed over rows of gas flames or between heated metal plates to avoid any burning of the yarns. Singeing cannot be used for fabrics made from thermoplastic fibers as this will result in melting the fibers. Fabrics made from continuous filaments do not require singeing. With wool fabrics, shearing or fiber clipping is used as singeing of wool fibers can result in strong sulfur odor. The main purpose of singeing is to create a smooth fabric surface and reduce pilling.

11.3.1.2 Desizing

Desizing is the process of size removal from the fabric to allow the application of other finishing treatments, particularly those that involve penetration through the fibers. The desizing process should be both efficient and environmentally friendly [1, 2, 5]. A key aspect in this regard is to recycle size materials for repeated use through efficient separation of the water from the size liquor during desizing. Scientists of BASF AG have developed a method in which synthetic sizes can be recycled in an environmentally friendly manner [5]. This method aims at reusing the size solution and the water repeatedly and without any loss of size effect. The name of the synthetic size used is "UCF-4." This new size material is claimed to have advantages over the traditional starch in many quality attributes such as chemical consumption, energy consumption, toxicity, emission, and risk potential. During desizing, UCF-4 can be removed effectively from the fabric by merely washing with hot water and without the addition of chemicals. This is achieved through efficient ultrafiltration process during recycling for separating the water and the size liquor. During ultrafiltration, the macromolecules of the size UCF-4 are held back by the membranes, while the water with its low molecular impurities from the fabric passes through the membrane.

This achieves a separation of high concentration size that can be reused for sizing new yarns and recovery of preheated water for the next desizing process. Using this size material, a recycling rate of over 80% is claimed without loss of size effectiveness.

The process of sizing and desizing of staple-fiber yarns for the sole sake of allowing the yarn to withstand the rigorous weaving process should invite joint efforts by scientists and engineers to seek ways to eliminate this entire process. Eliminating the sizing/desizing process should be the target of future development in spinning and weaving technology. This process adds substantial cost to the total manufacturing cost of woven fabric, most of which is divided into the cost of chemicals or add-on (about 80% of the cost) and the cost of energy consumption, particularly during yarn drying after sizing. The use of chemicals and the need to remove these chemicals yield unsustainable process. As indicated earlier, many developments have been made in making spinning and weaving machinery that are very efficient and largely automated. However, these developments are yet to result in a yarn that can exhibit surface and physical integrity, which allows it to be woven as spun and not via additional treatment to compensate for its deficiency. This problem provides a huge opportunity for creative engineering design ideas in this field.

11.3.1.3 Scouring

This is the process of removing impurities from the fabric. In natural fibers, impurities include oils, fats, waxes, minerals, leafy matter, and seed-coat fragments. These impurities are commonly removed by exposing the fabric to aqueous solutions of concentrated sodium hydroxide-containing detergents and then steaming and rinsing it [1, 5, 6]. In synthetic fibers, impurities can include spin finishes or oil contaminants from machinery. These are typically removed by extraction (dissolving in organic solvents), emulsion (forming stable suspensions of the impurities in water), and saponification (converting the impurities into water-soluble materials). For wool and silk, carbonizing and degumming processes are used to remove impurities. In carbonizing, vegetable matter is carbonized or destroyed using sulfuric acid. Degumming is the process of boiling silk fabric with soap to remove the sericin coating the silk filament.

11.3.1.4 Bleaching

This is a whitening process as most natural fibers exhibit off-white colors due to the presence of colored substances that can vary within the same fabric batch or between batches. Bleaching primarily destroys these color substances via applying oxidizing and reducing chemicals to decolorize and remove off-white substances from fabrics. Bleached fabric will exhibit consistent color after dying as a result of uniform dye uptake. Different fiber types will require different bleaching agents [1, 5, 6]. For cotton fabric, the common bleaching agent is hydrogen peroxide, buffered to maintain a pH of about 10.5. Wool fabrics are typically bleached using sodium peroxide solutions.

11.3.1.5 Mercerizing

This is the process of treating cotton fabric with caustic soda solutions at high concentration (19%–26%) to complete the removal of impurities initiated by scouring or bleaching [1, 5, 6]. Mercerization can substantially alter the appearance and the geometrical characteristics of fabric, making mercerized fabrics uniquely different from unmercerized fabrics. This is because caustic soda solution results in cotton fiber swelling, breaking hydrogen bonds and weak van der Waal forces between cellulose chains, and leaving the cellulosic chains (after removal) in a reorganized state. Mercerization can be applied in a relaxed state or under tension. The former will result in fiber swelling (coarser and shorter fibers) and fabric thickening. This leads to stronger and more elastic fabric. The latter results in orienting the fibers along their axes making them more rounded (rodlike cross section) and leading to smoother and higher-luster fabric. It also results in a significant increase in strength (about 35%) by virtue of fiber orientation. In addition, the fiber also becomes more absorbent as a result of the change of cellulose crystal unit cell from cellulose I to cellulose II and increase in openness of the amorphous area [6]. Therefore, mercerized cotton will absorb more dye and more water than unmercerized cotton.

11.3.2 Examples of performance-enhancement finish

11.3.2.1 Moisture management: Water repellency, waterproof, and hydrophilicity

Moisture management is a key performance characteristic in many fibrous products such as water-repellent fabrics, waterproof fabrics, stain-resistant fabrics, and comfort products. A water-repellent fabric is a fabric that simply resists water penetration through the fabric construction. This is not to be confused with waterproof fabric, which is completely water and air resistant. From a design viewpoint, water repellency can be achieved through optimization of many parameters [3]. Fabric-related parameters include fabric construction, fabric density, and cover factor. Yarn-related parameters include yarn type, yarn count, and yarn twist. Fiber-related parameters include fiber type, fiber fineness, fiber absorption characteristics, and fiber wicking characteristics.

The role of fabric finish is to further enhance water repellency [5–7]. Chemical finishes used for this purpose are typically hydrophobic substances with a critical surface tension below that of the water as for fabric to be water repellent, the critical surface tension of the fiber surface should be below 30 dynes/cm (pure water typically has surface tension of about 72 dynes/cm). For oil repellency, lower fiber surface tensions will be required (below 13 dynes/cm). A common substance used for water-repellent treatments is paraffin wax, which is the most economical treatment. This can be applied using solvent solutions, molten coatings, or wax emulsions. This is not a permanent treatment as wax can be abraded by rubbing against other objects and dissolve in dry-cleaning fluids. Pyridinium compounds are also used as water-repellent treatment. These are long-chain fatty amides and wax resin mixture. Silicone

water repellents are also used for a variety of fabrics because of their durability as they exhibit high resistance to abrasion and they are less soluble in dry-cleaning fluids or laundry detergents. Fluorochemical repellents have the advantage of repelling both water and oil as a result of their low surface energy. These are very durable finish, and their application is mainly based on the reduction of the critical surface energy tension of the finished fabric surface to levels below that of the wetting liquid (in this case water). This creates a chemical barrier, which prevents penetration of the liquid. Of all textile chemicals, only fluoropolymers show this unique property of reducing surface energy to such an extent that they repel both aqueous and oily substances [7] (polar and nonpolar liquids).

A waterproof fabric is very highly resistant to water penetration even under high hydrostatic pressure. As in the case of water-repellent fabric, this feature will require special fabric construction of very tiny pores. The hydrophobic finish used to achieve this resistance is applied not only to the fibers but also to the fabric pores [1, 5, 6]. By definition, waterproof fabrics are unbreathable, meaning, just as they do not allow water drops from the rain to penetrate through the fabric, they also do not allow moisture vapor from perspiration to go through. However, unique design methods by engineers of GORE-TEX (https://www.gore-tex.com/) have resulted in fabrics that are waterproof and breathable. One of GORE-TEX ideas was to use a multiple-layer fabric system through placing a membrane of PTFE fluorocarbon underneath a layer of outer fabric and adding another lining fabric layer. According to GORE-TEX, this membrane has 9 billion microscopic pores per square inch that are 20,000 times smaller than a drop of water but 700 times larger than a molecule of water vapor. This allows moisture vapor from perspiration to pass through the fabric yet preventing rainwater drop from penetrating into the fabric. Other design aspects such as fabric construction and fabric seam closeness are taken into consideration.

Another approach of moisture management is to develop hydrophilic fabrics that can absorb water. These fabrics can be made from naturally hydrophilic fibers (cotton or wool). In addition, some chemical treatments including mercerization result in further improvement in the absorption characteristics of cotton fabrics. Fabrics made from synthetic fibers such as polyester can also be made hydrophilic using special finish such as sodium hydroxide solutions.

11.3.2.2 Oil-repellent and stain-resistant finish

Oil-repellent fabric is largely similar to the waterproof fabric. This requires very low surface tension of the fabric. The use of fluorochemical polymers results in fabrics that are both highly water resistant and highly oil resistant by preventing the fibrous material from being wetted and soiled, by repelling aqueous and oily soil particles, and by preventing adhesion of dry soil through antiadhesive properties [7].

Stain-resistant fabrics are treated with chemical blockers that depend on the type of potential stain [5–7]. For example, waterborne stains can be resisted using silicon water repellents. On the other hand, oil-based stains can be repelled using fluorochemical polymers that can prevent oils and water from penetrating into the fabric and soils from sticking to the fiber surface. This is particularly important for textile

products that are not routinely laundered such as upholstery fabrics and carpets. High-quality upholstery fabrics are expected to keep their pleasant appearance for a long time by being resistant to common stains in daily life such as coffee on the upholstered chair or jam on the sofa. It should be pointed out, however, that a conventional fluorochemical finish has its durability limitation, particularly in relation to abrasion resistance [5–7]. Abrasion effects can occur even under mild conditions such as seating and arm resting causing abrasion of the microfine fluoropolymer protection film that covers the fibrous material. This can result in a constant decrease in the stain- or soil-repellent effect.

11.3.2.3 Thermal-management finish

Thermal insulation of most fibrous products is commonly made using the basic principle of trapping air to reduce heat transfer particularly of convective and conductive modes [5–7]. This is a common approach, which is also used with other materials such as plastic foams and sintered refractory materials. The two key design criteria required for thermal insulation are (a) the rate of air flow (large cells trapped air will have internal convection currents) and (b) the amount of fiber material surrounding the air (large percentages of air entrapped between fibrous materials will result in a reduction of thermal bridging between fibers). These criteria can be satisfied using a combination of parameters including fiber type, yarn bulk density, yarn fineness, and fabric construction. Mechanical finishing processes that are known to influence thermal insulation are napping and brushing. In addition, special finishes can be applied using polymers that are temperature sensitive.

Unlike singeing, in which free fiber ends are removed, napping is a mechanical process to actually raise fibers from the body of the fabric using wire brushes. Fibers may be raised in an upright position or oriented in some direction. The raised fibers entrap air within the fabric surface creating an insulation layer between the fabric and human skin and create less contact between the skin and the fabric so that the loss of heat from the body by conduction can be reduced. Common napped products include [5–7] pajamas, blankets, sleepwear, sweaters, and baby dresses. Napped fabrics should not be confused with pile fabrics in which separate set of yarns, not fibers, is raised to create the pile. The napping process is facilitated by using yarns of low twist so that fibers can easily be raised from the yarns.

Brushing is a milder case of napping, which results in lower fiber density than that witnessed with napped fabrics. The purpose of brushing is also to provide warmth but at a lower efficiency than that of napped fabrics. Yarns used for brushed fabrics could have higher twist levels than those used for napped fabrics. Another way to achieve a fuzzy surface is through a process called “flocking” in which short fibers (rayon or nylon) are adhered to the fabric surface either on the entire surface or in pattern forms.

Thermally sensitive fabrics can also be made using chemical treatments that allow storing or releasing heat depending on the surrounding temperature [8, 9]. One of the familiar treatments is the use of polyethylene glycol (PEG) as a phase-change material (PCM). It has the ability to store excess heat at high temperature and release it at low temperature. Researchers of the USDA-ARS used PEG in combination with dimethyloldihydroxyethylene urea (DMDHEU), and some acid catalysts in a curing process to

create water-insoluble polymers that can be used as a phase-change finish of fabric. A phase-change fibers of PEG copolymers with polyethylene terephthalate (PET), can also be prepared by melt spinning [8, 9]. The PET/PEG copolymers have solid-solid phase-change characteristics at 10–60°C without obvious liquid substance appearing, while PET/PEG blends will lose their phase-change characteristics since the PEG of the blends may melt and leak under high temperature [8]. By controlling the molecular weight and relevant proportion of PEG added, the phase-change temperature range and the enthalpy can be adjusted. These treatments have great potentials for developing many products including some thermal underwear, surgical gowns, and socks.

Other developments in thermally sensitive fabrics include the following:

- The use of fibers with integral microspheres filled with phase-change material or plastic crystals that can enhance thermal properties at predetermined temperatures. These fibers can be woven to form fabrics of enhanced thermal storage properties [10].
- Coating fabrics with integral and leak-resistant microcapsules filled with phase-change material or plastic crystals that have specific thermal properties at predetermined temperatures [11].
- A thermoadhesive textile product of the type comprising a backing fabric and an adhesive layer deposited on its surface with the adhesive layer comprising a thermoadhesive polymer and a cross-linking agent that is isolated from the polymer by microencapsulation and freed by external action [12].

11.3.2.4 Antistatic finish

When two different surfaces come in contact, surface buildup of electrical charges can become a disturbing factor creating the so-called static charges. This can be serious particularly when one of the surfaces is a conductor, as this creates unlimited supply of electrons that can be transferred to the other surface. Previous treatments of fabric or the presence of electrolytic impurities can create these charges [5, 6]. Although most fibers particularly nylon, polyester, polypropylene, and acrylics are dielectric in nature (i.e., they are highly nonconductors), static charges can be generated during the various stages of processing and during the use of fibrous products. They can result from the rapid flow of fibers or fabrics against metallic guides. Excessive drag tension can be created when surfaces develop opposite charges leading to undesirable fiber or yarn stretch. Folding of fabrics can also be a problem when static charges are generated. In addition, the fabric can become a magnet to dust and other particles flying in the surrounding. When the fabric is converted into a garment, static charge often manifests itself in garment clinging to the body and dirt or lint attraction.

Finish treatments to minimize static charges include [6] the application of static control chemicals (e.g., 3M brand static control, aerosol sprays, and sodium hydroxide solution for acetate fabrics), friction reduction using lubrication, and blending fibers of potential opposite charges.

11.3.2.5 Flame-retardant finishes

For many years, the development of flame-retardant fabric has been one of the main concerns in the polymer and fiber industry. For traditional fibrous products such as children sleepwear, carpets, drapery, and upholstery, there is an obvious desire to have

products that do not ignite or create a self-sustaining flame when subjected to heat sources. For specialty products such as firemen or military uniforms, this desire is critical as exposure to fire is inevitable. The term flame retardant does not imply flameproof, as all fibrous products are likely to burn, melt, or char depending on the surrounding flammable situation and the period of exposure. However, some fabrics will tend to be more resistant than others. For example, a pile or napped fabric made from rayon or cotton is likely to be less flame retardant than a tightly closed woven fabric made from highly twisted yarn [3].

Flame-retardant fabrics can either be developed from fibers that are inherently flame resistant or be applied as a suitable finish that can slow down the burning process [6]. Many flame-resistant traditional fibrous products are made from inherently flame-resistant fibers with the help of fabric construction factors. Specialty fibrous products are often topically treated with flame-retardant finish. In recent years, new chemical finishes have been developed to treat fabrics of both categories for flame-resistant applications. From a design viewpoint, applications of these finishes and their add-ons must be optimized as they may adversely affect other performance characteristics in the fabric. Examples of flame-retardant finishes include [6] a mixture of boric acid/borax (sodium borate) for cellulosic fibers, phosphorus-based flame retardants, and sulfamic acid and ammonium sulfamate.

11.3.2.6 Antimicrobial finished fabrics

Antimicrobial activity can be defined as a collective term for all active principles (agents) that inhibit the growth of bacteria, prevent the formation of microbial colonies, and may destroy microorganisms. In the field of antimicrobial finish, many common terms are used including antibacterial, bactericidal, bacteriostatic, fungicidal, fungistatic, biocidal, and biostatic. According to Mucha et al. [13] of the Hohenstein Institute, antimicrobial activity refers to a situation where an active agent has a negative effect on the vitality of microorganisms. If the active agent only affects bacteria or fungi, this is referred to as antibacterial or antimycotic activity, respectively. The degree of the effect is denoted by -cidal (or lethal) where there is significant germicidal activity or -static where the active substance serves to inhibit the growth of bacteria. Accordingly, the term bacteriostatic refers to an agent, which temporarily inhibits the growth of a specific bacterial population without destroying this population or without being able to multiply to any significant extent. The authors add that as yet, there is no universally accepted definition as to what constitutes significant growth or reduction in the bacterial colony. The ideal requirement of a biostasis is that a defined bacterial population remains constant in terms of its size. In practice, however, this is extremely rare as vital biological systems are in a sensitive dynamic equilibrium and react to any change in their life system by either growing or dying.

Antimicrobial finish treatments are commonly used in specialty fibrous products of protective nature. However, the increasing awareness by consumers of hygiene-related issues has resulted in extending the use of these treatments to many consumer products. These treatments primarily aim at avoiding the adverse effects of microbial fiber degradation, limiting the incidence of bacteria, reducing the formation of odor as

a result of the microbial degradation of perspiration, and avoiding bacterial infection. In practice, antimicrobial finish can be used in numerous applications, particularly for the sake of protecting fibrous products from the effects of microbes specially the fungi type. Products that can be protected include uniforms, tents, geotextiles, curtains, and bath mats.

One category of common finish agents is that of liquid additives known as sanitizers. These are used in the final rinse of laundry particularly for clothing worn against the skin. In applications such as outdoor and sporting, it is important to prevent the buildup of odors on clothing. In these situations, antimicrobial agents act to prevent the microbial decomposition of perspiration on the clothing (or prevent the release of odorous substances).

Antimicrobial fibrous products can be divided into two categories [7, 13]: passive and active products. Passive products do not have specific bioactive substance. They rely on fibers that are inherently antimicrobial (e.g., hydrophobic fibers with special surface morphologies such as lotus-like or microdomain structured surfaces). In this category, bacterial cells are prevented from being adhered to the fiber surface by virtue of the surface structure and the low absorption of fibers. Active products contain specific antimicrobial finish that can attack microorganisms. These are highly specialized agents that target specific microorganisms. Many of these finish agents have been known for years in the food and cosmetic industries. Common antimicrobial agents include oxidizing agents (aldehydes, halogens, and peroxo compounds), ammonium compounds (amines and glucoprotamine), metallic compounds (silver), and natural products (chitosan). Key criteria of these agents include low toxic risk and resistant to washing and dry cleaning.

11.3.2.7 Durable-press finish

Fabrics made from most synthetic fibers are inherently wrinkle free, meaning they can be washed, dried, and worn without a need for ironing as they have good shape and appearance retention. Durable-press finish is primarily used to maintain the dimensional stability of some fibrous products, particularly cotton and wool products, after washing. The relationship between dimensional stability and moisture is well established, particularly when hydrophilic fibers are used [1, 6]. Basically, dimensional instability is a result of the effect of water on the molecular structure of fibers under external stresses. In the case of cotton, the mechanical stresses imposed by the washing process break the hydrogen bonds between adjacent molecular chains. The presence of water facilitates the slippage between the molecular chains and forms new bonds (reassociation of hydroxyl groups). This new molecular configuration is difficult to recover upon drying unless external effects such as ironing are applied.

A common approach to provide wrinkle-free characteristics to cotton and wool fibers is by blending these fibers with synthetic fibers [3, 4]. When fabrics are made purely from these fibers, durable-press finish is typically used to provide wrinkle-free features to them. For example, cotton and other cellulosic fabrics are treated with durable-press resins [1, 5, 6], which eliminate the need for starch and ironing. These fabrics should be washed carefully in cold water, as durable-press (or loosely

called permanent-press) chemicals may not be so durable in hot water environment. Durable-press finished products include sheets, pillowcases, some shirts, and blouses. Some 100% cotton pants are also wrinkle free as a result of the applications of appropriate chemicals that create cross-linking effect in the cellulosic chains. The merits of these chemicals often come at the expense of deteriorations in critical performance characteristics such as flexibility, tenacity, elongation, and abrasion resistance. This is one of the reasons that blending cotton with polyester to develop durable-press fabrics is often a better alternative as polyester fibers, being unaffected by the durable-press resins, can compensate for these deteriorations. Another approach to reduce these deteriorations is to treat cotton with liquid ammonia to strengthen the cotton fiber prior to the durable-press treatment. Mercerization can also help in conjunction with permanent-press treatments through improving the strength of cotton fibers.

For wool fabrics, the so-called permanent set, in which sharp pleats and creases are permanently inserted, is applied to the fabric to create wrinkle-free wool [6, 7]. This is a result of a chemical process in which heat and steam are utilized to provide ways for the bonded protein chains to exhibit relative movement, breaking hydrogen bonds by heat and steam, breaking disulfide bonds by chemicals, and allowing these bonds to reform in new positions when the fabric is set at a desired configuration. A wrinkle-free state is achieved when the bonds are allowed to reform.

11.3.2.8 Hand finish

In general, the term "fabric hand" describes the way a fabric feels when it is touched and manipulated by hand. It is an action noun that implies evaluation of fabric reaction to different modes of low-stress deformation imposed by human hand. Another term that is commonly used in the industry is "fabric handle." This is an action verb that reflects the evaluation of fabric reaction to different modes of deformation at all levels of applied stress (low or high).

Comparisons between subjective and objective measures of fabric hand revealed that the most important parameters constituting fabric hand are surface roughness (softness), fabric drape, bending stiffness, and compressibility [14]. From a design viewpoint, these parameters can be optimized through appropriate selection of raw material, yarn structure (count and twist level), and fabric construction (thickness and density). After forming the fabric, additional optimization of fabric hand can be achieved using many finish treatments. One of the common treatments for improving fabric hand is the use of softeners to give more pliability and smoother and softer feel to the fabrics. Softeners are divided into three major chemical categories describing the ionic nature of the molecule [5, 6]: anionic, cationic, and nonionic. Anionic softeners molecules have a negative charge on the molecule derived from either a carboxylate group (—COO—), a sulfate group (—OSO3—), or a phosphate group (—PO4—). Most softeners are of the sulfates and sulfonates types commonly used for cellulosic fibers and silk. These are basically negatively charged fatty acids and oils. Anionic softeners are often used for fabrics that undergo mechanical finish treatments such as napping or shearing. Cationic softeners (the common laundry fabric softeners) are ionic molecules that have a positive charge on the large part of the molecule. They also assist in reducing static charges on synthetic fibers. Nonionic

softeners can be divided into three subcategories: ethylene oxide derivatives, silicones, and hydrocarbon waxes based on paraffin or polyethylene.

11.3.2.9 Surface roughness finish

Surface roughness can be altered either for the purpose of modifying the feel of fibers or for modifying the surface characteristics and the visual appearance of fabric [15–17]. For instance, it is commonly known that some fibers such as polyester or polypropylene can be treated with delusterant such as titanium dioxide (TiO_2) to provide different levels of surface texture or surface irregularities and, consequently, different fiber appearance (fiber dullness). Based on the weight of the fiber, the inclusion of 1% delusterant can produce a "semidull" fiber, while doubling this amount would produce a "dull" fiber. Other studies treated nylon 66 fiber melt with TiO_2 to change the intensity of fiber luster and found that bright fibers (low TiO_2) tended to have a smooth surface whereas dull a rough surface [16]. This change in roughness was not accompanied by a chemical change in fiber surface, which remained essentially as that of the fiber material.

The titanium dioxide particles, roughly spherical of about 0.15-μm diameter (e.g., Ti-Pure R102 by DuPont), typically tend to adhere to each other forming agglomerate. Other types of filler particles of different shapes and dimensions are also used. These include [15, 16] calcium carbonate (parallelepiped, produced by Fisher Chemicals), NYAD 400 wollastonite (needlelike particles by NYCO Minerals Inc.), and talc JetFil 700C (discotic, Luzenac America, Inc.). Each of these particles produces a unique surface texture [17] and, therefore, affects other surface-related properties such as friction and abrasion resistance.

11.4 Nanotechnology: Finish applications

As indicated in the earlier sections, conventional finishing in the fabric form has been effective in providing many performance features such as water repellency, thermal insulation, antiodor/antiscent, and durable press. However, finishing in fabric form has also been associated with a number of challenges including manufacturing difficulty, alteration of physical and mechanical properties, poor durability, colorfastness problems, discomfort, low safety, and cost. More importantly, conventional finish has always been associated with problems related to its effectiveness, particularly in the context of add-on by weight or add-on by surface area covered with treatment. Nanotechnology or nanoscale engineering can provide solutions to many of these problems. Before proceeding with the discussion on this important aspect, it is important to provide the reader with a brief introduction on nanotechnology.

11.4.1 What is nanotechnology?

Nanotechnology can be defined as the technology of manipulating atoms and molecules at the nanometer scale (in SI units 10^{-9} m). The word "nano" is a Greek word, which means dwarf, or very small. It should be distinguished from the so-called

microtechnology, which indicates manipulation at the micrometer scale (in SI units 10^{-6} m). The full term "nanotechnology" was coined by K. Eric Drexler in his book *Engines of Creation* [18]. In general, engineers and scientists use the term "nano" to refer to physical quantities within the scale of a billionth of the reference unit. For example, nanometer, nanosecond, nanogram, and nanofarad are used to describe a billionth of a meter (length), second (time), gram (weight), and farad (charge), respectively.

As a derivative of nanomaterials, some fibers are classified as "nanofibers." This may be defined as one-dimensional nanoscale element, which falls under the general category of nanotubes and nanorods (very tiny diameter) but exhibits exceptional flexibility as it is the case of conventional fiber. Indeed, the flexibility nature of nanofibers often results in placing them in the category of other nanoflexible elements such as globular molecules (virtually, zero-dimensional soft matter) and solid and liquid films of nanothickness (two-dimensional elements). Some fibers that are filled with nanoparticles are also called nanofibers, while they are more of composite nanofibers. The manufacturing of nanofibers can belong to one of two major categories of nanotechnology, namely [18, 19], the top-down (the act of removal or cutting down a bulk to the desired nanosize) and the bottom-up nanotechnologies (developing nanofibers using fundamental building blocks such as atoms and molecules). These technologies are now commercially available, and they include drawing, template synthesis, phase separation, self-assembly, and electrospinning. Discussion on these technologies is outside the scope of this book.

In the context of finishing, nanotechnology can be used to modify conventional textile fibers at the nanolevel so that function-focus tasks can be performed without apparent changes in the inherent physical characteristics of the fibers. Perhaps, the key potential advantage of this technology stems from the possibility of developing a smart material that has the ability to transform or yield its properties to particular external stimuli. Technologies associated with nanochemistry and nanomaterial are related to material composition and interface structure, control of size between 1 and 100 nm, and transformation of material to acquire special characteristic properties. Such technology is applied to optoelectronic, electronic, energy storage, and semiconductor fields to develop new materials and key components. Related technologies also include those for nanochemical synthesis, nanostructure, performance simulation, and measurement or testing of nanomaterials.

11.4.2 Examples of nanofinishes

11.4.2.1 Antiodor and antimicrobial additives

One of the interesting applications of nanotechnology is the use of silver at the nanoscale to provide antiodor and antimicrobial functions to the fabric [18–20]. Since antiquity, silver has been known as an antimicrobial (silver dishes and chalices were used to preserve food in ancient Greece). Over the last century, silver has even been used in modern medicine to act as a disinfectant in children's eye drops and in numerous other applications, such as lining water holding tanks in boats and airplanes to

ensure safety for drinking for up to several months. This has resulted in consideration of this important material in developing antimicrobial finishes for fibers. In contrast with many nonpermanent antimicrobial chemicals that require special handling due to their toxicity, silver is considered as one of the natural and far safer alternative. However, silver has its own drawbacks including cost, permanence, and manufacturability. Silver-coated fibers are expensive and difficult to use and shed silver flakes, reducing effectiveness and creating potential effluent problems. For example, the so-called "nanosilver" powders applied during spinning tend to clog extruding spinnerets, do not bond well to polymers or cotton, and generate airborne silver dust [3].

As a result of the difficulty associated with using silver powders, a product called SmartSilver was developed by NanoHorizons Inc. (https://www.azonano.com). This is a line of permanent antiodor/antimicrobial additives that can be used for treating fibers such as polyester, cotton, nylon, and polyurethane. This type of treatment takes place at the molecular level. According to NanoHorizons Inc., smart silver-modified fibers can be used to create odor-resistant shoe linings, T-shirts, socks, gloves, carpets, and more. Urethane applications include rainwear, upholstery, paints, caulks, and other coatings for which SmartSilver adds odor resistance and resistance to mildew and mold growth. SmartSilver is also claimed to not alter stretch, wicking, hand, or dyeability of fibers and fabrics, enabling designers to add permanent and effective antiodor properties to fabrics and fibers.

The principle underlying the use of silver as antimicrobial components is that silver nanoparticles take advantages of the oligodynamic effect that silver has on microbes, whereby silver ions bind to reactive groups in target cells or organisms, resulting in their precipitation and inactivation. In simple words, this means that silver ions generated by exposed silver surfaces are highly lethal to microbes in several different ways. In fact, microbes generally have a harder time developing resistance to silver than they do to antibiotics. The key to using silver effectively is to find a way to maximize the production of silver ions in a particular application. From a design perspective, one approach is to increase the weight of silver being used. This is an expensive and performance-hindering approach. Alternatively, maximization of silver ion release can be achieved by generating as much surface area as possible. This can be achieved more effectively at the nanoscale. The greater the extent to which microbes are exposed to the silver ions generated by silver surface area, the more they can interact with these ions leading to their destruction.

11.4.2.2 Water- and stain-repellent nanotreatments

As indicated earlier, water or stain repellence requires surface treatment with chemicals that yield a very low surface tension of the fabric such as fluorochemicals. At the nanoscale, surface wetting can be controlled through a special design in which the relationship between surface roughness and surface reaction to liquid drops is optimized. This relationship stems from the so-called "lotus" effect, a unique natural effect that clearly demonstrates the aspect of mimicking natural phenomena in the development of specialty products. It will be important, therefore, to dwell on this

subject to give the reader a greater insight into how nature could represent a major source of design ideas.

The relationship between surface wetting and surface roughness

The equilibrium shape of a liquid drop on a surface is governed by three basic forces existing at three interfaces [21–25]: these are the solid/liquid, *SL*; liquid/vapor, *LV*; and solid/vapor, *SV*, surface tensions. The balance of these tensions yields the well-known Young's equation (see Fig. 11.1):

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta$$

where θ is called the intrinsic contact angle of the drop and is a parameter that reflects the degree of wettability of a surface. A surface that is wettable for a given fluid has θ less than 90 degrees, and the closer the value to zero, the more rapidly wettable the surface. The role of surface roughness in influencing wettability is given by the Wenzel equation [22] as follows:

$$\cos\theta_{\text{rough}} = r \cos\theta_{\text{smooth}}$$

where r is called roughness factor defined by the ratio of rough to planar surface areas.

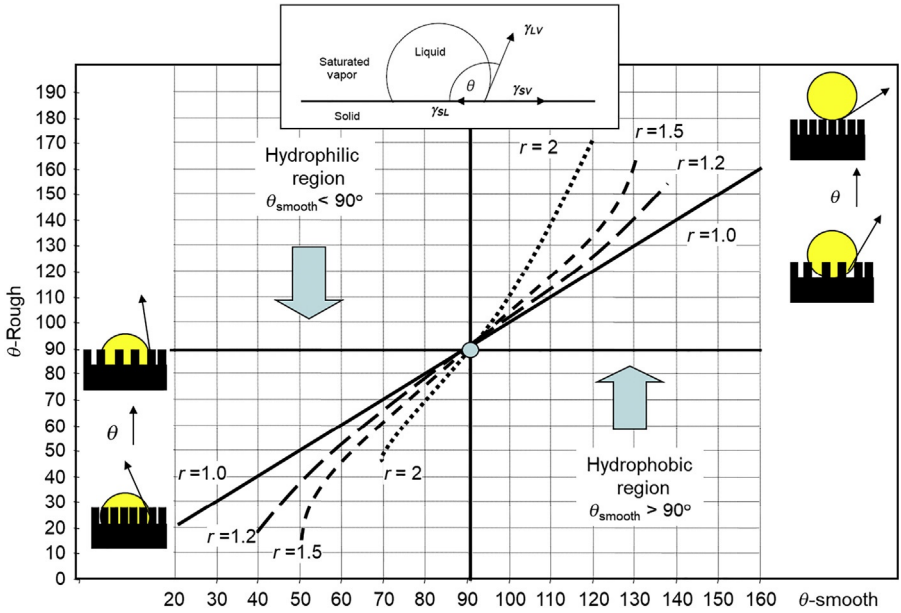


Fig. 11.1 Demonstration of Young and Wenzel models [21–25]. In the hydrophilic material (*left*), as r increases from 1 to 2, θ decreases. In the hydrophobic material (*right*), as r increases from 1 to 2, θ increases.

The aforementioned equation indicates that for a rough surface ($r > 1$), wettability is improved by roughness of a hydrophilic surface ($\theta_{rough} < \theta_{smooth}$ for $\theta < 90°$), and hydrophobicity or dryness is improved by roughness of a hydrophobic surface ($\theta_{rough} > \theta_{smooth}$ for $\theta > 90°$). This theoretical concept agrees with physical observations; a drop on a rough high energy surface will likely to sink into the surface. For $\theta > 90°$, the free energy of the dry surface is lower than that of the wet solid, and hence, the drop will likely recede from the roughest regions.

In an early study by Cassie and Baxter [23], a rough surface was modeled by a heterogeneous surface composed of air pockets and the solid. They postulated that the cosine of the contact angle of a liquid drop on a heterogeneous surface corresponds to the sum of the cosines of the contact angles of the two homogeneous materials, weighted by the amount of available surface. If one of the surfaces is just air, the cosine of the contact angle on this surface is -1, leading to the following equation:

$$\cos\ \theta_{rough} = -1 + \phi_S(1 + \cos\ \theta_{smooth})$$

where φ_s is the surface fraction of the solid. A very rough surface will have a φ_s value approaching zero and, therefore, a rough contact angle approaching 180 degrees; accordingly, the liquid drop will theoretically lift off the solid surface.

In summary, for the equilibrium configurations of liquids on rough surfaces, if the surface has a high interfacial energy, roughness promotes wetting, and the liquid will spread within the corrugation (surface wicking). But for a low energy surface, roughness promotes repulsion: the drop does not follow the surface corrugations but achieves its minimum at a position on top of the corrugation. This represents the basis for self-cleaning surfaces.

The question of "how can surface texture be manipulated to enhance the cleanability of hydrophilic and hydrophobic surfaces?" has been the focus of many design activities of fibrous products, particularly those implemented in the field of biotechnology in which clean surfaces is an essential requirement. For the case of hydrophilic materials, cleaning is basically a process of causing contaminant film to flow. In this case, numerous factors may influence cleanability. These include [23–25] the ability of the liquid to dissolve the contaminants (solution/contaminant chemical compatibility), the ability of the liquid to adhere to the contaminants, the pore structure (pore size and its distribution) of the hydrophilic surface, the contaminant particle size and its distribution, the extent to which the capillaries are blocked by unforeseen chemical reactions, and liquid characteristics. These aspects are considered in the design of many fibrous products such as filters and reusable absorbent medical fabrics.

In the context of surface texture, it was indicated earlier that if a material has a high surface free energy, roughness promotes wetting, and the liquid will flow within the corrugation. When contaminants are present and assuming no chemical interaction between liquid and contaminants, any removal of contaminant particles will depend largely on the sliding pattern of the liquid against the surface. This is because contaminants should be transported along the surface for efficient cleaning. For this, surface texture can be manipulated to accelerate planar sliding pattern from a liquid. This can be achieved by modification of surface during spinning or by application of special finish.

The "lotus" effect

For the case of hydrophobic surfaces, a fascinating phenomenon was discovered by two botanists, Barthlott and Neinhuis from Bonn, Germany, in the course of their studies of plant leaf structures [24, 25]. They noticed that surface features of the lotus leaf, together with its waxy surface chemistry, rendered the leaf nonwettable. Indeed, the surface of the lotus leaf is one of the nature's most water-repellent surfaces. As seen in Fig. 11.2A, the surface has countless miniature protrusions coated with water-repellant hydrophobic substance. As a result, the water droplets form spherical globules and roll off the leaves even when they are only slightly inclined. Particles of dirt absorbed by water are removed in the process as shown in Fig. 11.2B. Note that in comparison with human skin, another hydrophobic surface with a contact angle of about 90 degrees, the lotus leaf exhibits a contact angle of 170 degrees. Bird feather, another superhydrophobic surface, has a contact angle of about 150 degrees.

The lotus leaf exhibits a unique porous surface texture on a micrometer scale. The air trapped in the crevices prevents water from adhering to the solid. Researchers led by H. Yildirim Erbil of Kocaeli University in Turkey [26] recreated such superhydrophobic surface by first dissolving polypropylene in a solvent and then adding a precipitating agent and applying the solution to a glass slide. After evaporating the solvent mixture in a vacuum oven, they had a highly porous gel coating with a contact

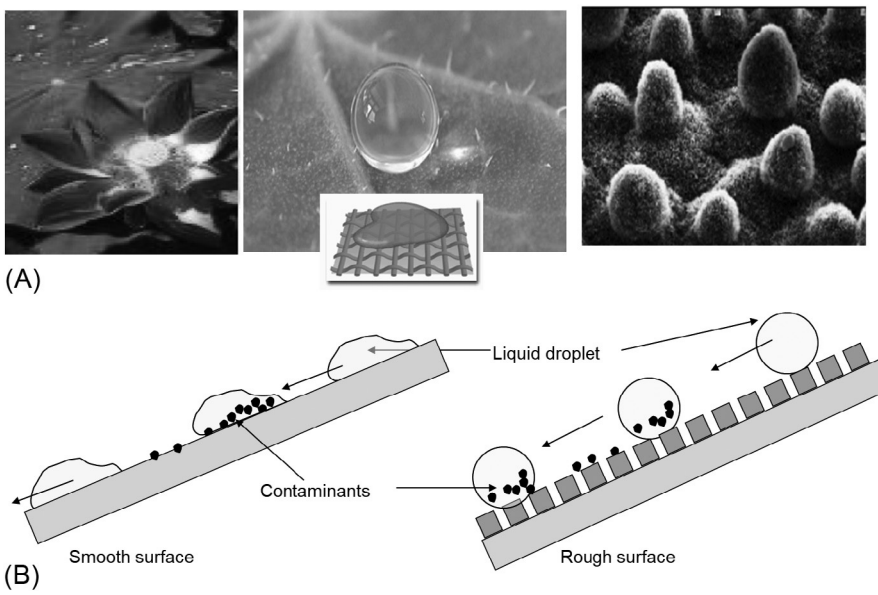


Fig. 11.2 The "lotus" effect [24, 25]. (A) Macroscopic and microscopic lotus leaf surface and (B) water movement against smooth and rough hydrophobic surfaces.

angle of 160 degrees and water-repelling capabilities comparable with those of the lotus leaf.

In another study, Luzinov et al. [27] examined a number of approaches for mimicking the behavior of lotus leaf to create synthetic coatings with exceptional antiwetting properties. They employed combination of polystyrene-grafted layer (low-surface-energy component) and nanoparticles (roughness initiation component) and obtained a textile material that demonstrated very low wettability by water. They also attempted to create the "lotus" effect on a fabric surface by evaluating the deposition of both polystyrene (PS) and triblock copolymer polystyrene-b-(ethylene-*co*-butylene)-b-styrene (SEBS) simultaneously on a model substrate. Polystyrene was then extracted employing selective solvent, ethyl acetate, which acted as a solvent for PS and as a nonsolvent for SEBS. The dissolution of PS created a porous (rough) hydrophobic structure on the substrate. The controlled method of surface modification was applied to a polyester fabric, which produced a practically nonwettable textile product.

On the commercial side, nanotechnology has been used to mimic the lotus effect for some fibrous products. For example, the so-called Nano-Care for cotton, developed by Nano-Tex uses "nanowhiskers" 1/1000 the size of a typical cotton fiber attached to the individual fibers. The changes to the fibers are undetectable and do not affect the natural hand and breathability of the fabric. The whiskers cause liquids to roll off the fabric. Semisolids such as ketchup or salad dressing sit on the surface, are easily lifted off, and cause minimal staining, which should be removed with laundering. In addition to the stain resistance attributes typically provided by conventional finish treatments, Nano-Care is claimed to allow moisture to pass through the fabric (e.g., quick drying). Nano-Tex also developed Nano-Dry technology to provide wickability and moisture absorption properties for nylon and polyester fabrics. This can be used for many products including high-performance outerwear.

The dynamic behavior of droplets on ultrahydrophobic surfaces was studied in great detail by David Quéré of the Collège de France and his collaborators [28–33]. Their research indicated that the most important effect of these surfaces on liquid drops concerned the contact line of the drop; that is the one-dimensional line of intersection of the three interfaces. Because the contact area of the drop shrinks with an increase in contact angle, the contact line can be deformed less easily, and hence, the hysteresis in contact angle between the advancing angle (θ_a, or the front angle in direction of droplet motion) and the receding value (θ_r, or the rear angle) is drastically reduced. This hysteresis is expressed by the pinning force per unit length of the drop perimeter:

$$F = \gamma_{LV}(\cos\theta_r - \cos\theta_a)$$

This force must be overcome by external forces (wind, gravity, etc.) to initiate droplet motion. If the hysteresis is too large and the driving force is not big enough, the liquid drop will stick or be smeared across the surface. If the contact angles are sufficiently high ($>$ 170 degrees) viscous droplets will roll off the surfaces (not slide).

The dynamic contact angles of a drop moving down a surface are affected by the magnitude of surface roughness [34]. For surface projections of several tens of micrometers, a liquid droplet can still be deformed by them even if it is considerably larger than the projections themselves. Therefore, smaller projections are generally needed for a good ultrahydrophobic surface.

Another important factor affecting the dynamics of a drop on an ultrahydrophobic surface is the velocity of impact. Typically, the impact of the liquid droplet against a surface will result in an elastic rebounding with a velocity almost equal to that of impact. This information is useful in designing repellent or drying surfaces.

The self-cleaning mechanism of ultrahydrophobic surfaces relies on the smallness of the contact area of a drop on a surface. For the ultrahydrophilic route to self-cleaning, the flow of the liquid film is essential. Ultrahydrophilic surfaces are wetted easily with very low-contact-angle fluids: if the surface is inclined, it is the flowing liquid film that carries the contaminants along. The usefulness of this concept thus depends on the rapidity with which a liquid film runs off a surface. For sufficiently thick films (of the order of hundreds of nanometers and above), flow is hydrodynamic. For thinner films, however, the flow of the film will consist of a rapid equilibration by surface diffusion. Not all liquid will move; there will be a stagnant (solidified) layer on microscopic scale.

11.5 Coating and lamination

The concept of fabric finish can be extended to cover a unique area that has become an independent sector of the industry due to its critical importance particularly for function-focus fibrous products. This area is coating and lamination of fabric [35–39]. Coating is basically a surface treatment of fabric using some form of polymeric viscous liquid that is after drying or curing (to harden the coating) forms a solid coat distributed evenly over the fabric surface. The idea here is not to block the inherent characteristics of the fabric but rather to enhance it using coating materials that can provide added functions to the fibrous end product via the surface. The polymeric liquid can be a polymer melt that can be cooled for hardening and solidification or a polymer solution, which upon cooling forms a solid film by evaporation of the solvent. Other types of coating can be applied in the liquid form and then chemically cross-linked to form a solid film [35]. Examples of coating substances and their merits are listed in Table 11.1. Note how different coating polymers provide special functions to the fibrous materials.

Lamination is basically an adhesive material combining two or more fabrics (textile laminates). Many types of adhesives can be used depending on interfacial compatibility and environmental factors. Hot-melt adhesives are believed to be one of the most environmentally friendly adhesives. It is also energy efficient and produces more permanently bonded laminates at a higher speed. Polyurethane foam is still used in thin layers using the so-called flame bonding. Although this process produces gaseous effluent, it typically gives a desirable bulky appearance of final products.

Table 11.1 Examples of common coating materials and their functions [35–39].

Coating substance	Description and functions
Polyvinyl chloride (PVC)	– To be used as a coating material, it must be transformed into a soft flexible film – The powdered PVC polymer can absorb large quantities of nonvolatile organic liquids called plasticizers. It can absorb as much as its weight from cyclohexylisooctylphthalate (a typical plasticizer) – The flexibility of the resultant film can be varied by the amount of plasticizer added – PVC coating is resistant to acids and alkalis, but organic solvents can extract the plasticizer, making the coatings more rigid and prone to cracking – Plasticized PVC forms a clear film that has good abrasion resistance and low permeability – The film may be pigmented or filled with flame-retardant chemicals to yield low flammability – Large dipole and high dielectric strength. This allows the coated product to be joined together by both radiofrequency and dielectric welding techniques. This factor makes it ideal for protective applications
Polytetrafluoroethylene (PTFE)	– Discovered by DuPont in 1941 – Manufactured by the addition polymerization of tetrafluoroethylene – Very low surface energy (water and oil repellence) – The polymer has excellent thermal stability to up to a temperature of 250°C – Resistant to most solvents and chemicals, but it may be etched by strong oxidizing acids (which is a feature that can be used to enhance adhesion applications)
Natural rubber	– A linear polymer of polyisoprene – Rubber emulsion can be used directly for coating, or the polymer may be coagulated and mixed at moderate temperatures with appropriate fillers – Natural rubber contains unsaturated double bonds along the polymer chain. These may be cross-linked with sulfur (i.e., vulcanization process) to give tough abrasion-resistant films or hard ebony-like structures. Cross-linking rate can also affect the rubber flexibility – Vulcanized rubber coating is commonly used for tires and belting to provide excellent abrasion resistance
Styrene-butadiene rubber (SBR)	– Made by the emulsion polymerization of styrene and butadiene – It is not used for tire coating because of its relatively poor resilience compared with natural rubber – It is used for fabric coating to provide superior weather and ozone resistance

Continued

Table 11.1 Continued

Coating substance	Description and functions
Polychloroprene (neoprene)	– Used as a substitute for natural rubber in many applications – It is made during the emulsion polymerization of 2-chlorobutadiene – It can be vulcanized and show tensile properties similar to natural rubber – It is famous for its excellent oil resistance, weathering, and ozone resistance (belts and hoses applications)
Silicone rubber	– Silicone rubber is a unique synthetic elastomer made from a cross-linked polymer that is reinforced with silica – It provides an excellent balance of mechanical and chemical properties required by many industrial applications – Water resistant – Chemical resistant – Good release properties – Good adhesion – Wide operating temperature range (−50 to +300°C possible) – Superior cold resistance (specialty silicone rubber grades can perform at temperatures as low as −85°C) – Better retention of tensile and elongation properties after heat aging – Relatively high surface friction (useful for some applications such as conveyor belts) – Resistant to weathering and UV rays – Can be made flame resistant
Polyurethanes	– Polyurethanes are made by the reaction of a diisocyanate with a diol – Polyurethanes used for coating textiles are frequently supplied as an isocyanate-tipped prepolymer and a low-molecular-weight hydroxyl-tipped polyester, polyether, or polyamide – The two materials will react at room temperature although this is often accelerated by raising the temperature – Polyurethane coatings show outstanding resistance to abrasion combined with good resistance to water and solvents; in addition, they offer good flexibility

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Basic attributes of textile products

12

12.1 Introduction

In Chapter 3, product development cycle was described by seven critical phases. The most critical phase was identifying performance characteristics and related attributes. The difficulty of this phase stems from the fact that a performance characteristic of a textile product is hardly a direct property that can be measured and embedded in a product in a systematic fashion to make the product perform according to its expectation. Instead, it is often a complex function of a combination of basic attributes of the different elements (fiber, yarn, and fabric) constituting the end product within the structural boundaries of these elements. In other words, a performance characteristic stems from an appropriate product assembly leading to a combination of different attributes that collectively yield the required performance. Examples of performance characteristics include aesthetics, comfort, and durability. These characteristics are highly recognized, yet they cannot be measured or described by a single parameter. As a result, they are often assumed, produced by experience, and not engineered-in or designed-in.

It is important that both the elements of the product assembly and their measurable attributes are harmonized so that their integral outcome can lead to an optimum level of the desired performance characteristic. For example, if durability under tension is the desired performance characteristic, the selection of a fiber type exhibiting high strength will represent a key element/attribute combination. When the fibers are converted into a yarn, the new fiber assembly should still meet the same level of strength or enhance it. In this case, the new element/attribute combination to be optimized is yarn structure/yarn strength. As the yarn is converted into a fabric, construction/strength combination of fabric should be optimized. Finally, fabric finish must be carefully selected and applied in such a way that can enhance durability or minimize any side effects that can lead to deterioration in this critical performance characteristic.

Most material attributes can easily be tested using standard techniques. These include weight, thickness, strength, thermal properties, and electrical properties. Performance characteristics, on the other hand, are often more difficult to test because they describe responsive behavior to specific uses or certain levels of external stimuli (environmental or mechanical). This makes it often difficult to standardize tests for performance characteristics that can reflect all applications that a product may be used for. Accordingly, they should be assessed in more simulative manner. This means that reliable simulation techniques to resemble the product performance must be incorporated in the product development cycle. This is one area where the textile industry is far behind in terms of development. In the absence of these

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techniques, design approaches in the textile industry will continue to be largely subjective and trial-and-error based, which can be very costly.

The process of transforming basic attributes into performance characteristics is primarily an engineering task since it requires development of a design-problem model as explained in Chapter 5. This is where textile science and textile engineering should be clearly differentiated. Textile scientists normally focus on the description of basic attributes of fibrous materials and the structures of fiber assemblies. Textile engineers, on the other hand, should focus on transforming basic attributes and structural features into predefined performance characteristics of textile products and ultimately determining the levels of attributes that can result in an optimum value of the desired performance characteristic. It is the author's opinion that this distinction is not clearly emphasized in most textile education institutions, and this often leads to ill-defined descriptions of textile careers.

In the design conceptualization phase, the performance characteristic of the intended product represents a key aspect in defining the design problem. As indicated in Chapter 4, there are two categories of design-problem definition: a broad definition and a specific definition. The broad definition of a problem should be driven by the general performance characteristics of the product. For most traditional textile products, general performance characteristics will include durability, comfort, aesthetic, care or maintenance, and health or safety characteristics. The extent of meeting each of these characteristics will depend on the type of product under consideration. The specific definition of a design problem stems from some specifications dictated by the product user or some specialty function(s) that must be highly emphasized in the design process to meet the expected primary performance. For example, apparel textile products should exhibit acceptable durability levels below which the product will not be acceptable. They should also provide comfort to the wearer. Accordingly, durability and comfort are often considered as basic performance characteristics in the broad definition of the design problem. When an apparel product is used for specific applications (e.g., military uniform or sportswear) in which high levels of physical activity or variable environmental conditions are anticipated, specific definitions of the design problem should then be stated. These definitions should be associated with more precise list and more specific values of performance characteristics. For example, a more specific definition may imply the exact level of fabric strength below which the product will not be acceptable or the tolerance allowed for thermal insulation.

12.2 Modeling performance characteristics: Backward projection analysis

In Chapter 5, the lack of implementing quantitative design approaches in the textile industry was discussed. According to Hearle [1], "while other industries marched into the second half of the 20th century utilizing more quantitative design approaches inspired by the growth of the science of applied mechanics and the theory of elasticity, these approaches were not transformed to the textile industry, which continued to

implement empiricism and augmented the qualitative insights in its product design applications, with the one exception being the mechanical and power-driven design of textile machinery." It is the author's opinion that quantitative design approaches can only be taken through developing performance models of textile products that can yield reliable relationships between the relevant attributes and the desired performance characteristics of textile products. Over the years, many attempts have been made to develop such models including the early studies by Peirce [2–4] to model water vapor permeability and heat transfer through fabric structures and explore the geometrical structures of functional fabrics, then the work by Hearle et al. [5,6] on tensile and elastic behavior of yarns and fabrics, and then the work by Kawabata [7] on plain weave fabric models. These models are still useful today for exploring the performance characteristics of textile products. However, their utilization in design applications is limited by the many assumptions made to develop idealized models and their lack of predictive power that can assist in solving design problems and reaching optimum performance characteristics.

In order to develop attribute-performance models that can be used in design applications, a backward projection analysis should be implemented using the following steps:

1. Identifying and defining the desired performance characteristics of the end-product assembly
2. Analysis of different fabric attributes that can lead to the desired performance characteristics
3. Analysis of different yarn attributes that can lead to the anticipated fabric attributes
4. Analysis of different fiber attributes that can lead to the anticipated yarn attributes
5. Selection of the appropriate fiber that can satisfy the required fiber attributes

The earlier sequence is described by the general performance-attribute diagram shown in Fig. 12.1. This diagram is developed with focus on product durability. As illustrated in this diagram, the starting point is analysis of the end-product assembly by breaking down the expected performance characteristic of the product assembly into related attributes of the fabric. The second step is to develop relationships between relevant fabric attributes and the yarn properties that are most likely to influence these attributes. The third step is to develop relationships between relevant yarn attributes and the fiber properties that are most likely to influence these attributes. This type of backward projection analysis is essential in design projects.

Backward projection analysis should also be associated with the evaluation of the cost profile of the different fibrous elements constituting the end product. Cost analysis in the textile industry has traditionally been based on production cost data. This approach may be useful in optimizing manufacturing cost, but it often results on focusing on material price rather than material value. Typically, the price of fibers contributes a range from 60% to 70% to the total manufacturing cost of textile products. Natural fibers being largely commodities are priced based on the supply and demand rules. On the other hand, synthetic fibers are often priced in view of the natural fiber market price. Cotton and polyester fibers being the fibers enjoying the largest market share of all fibers (over 60%) will typically have comparable prices particularly in the production of traditional textile products. In engineering textiles, the key aspect

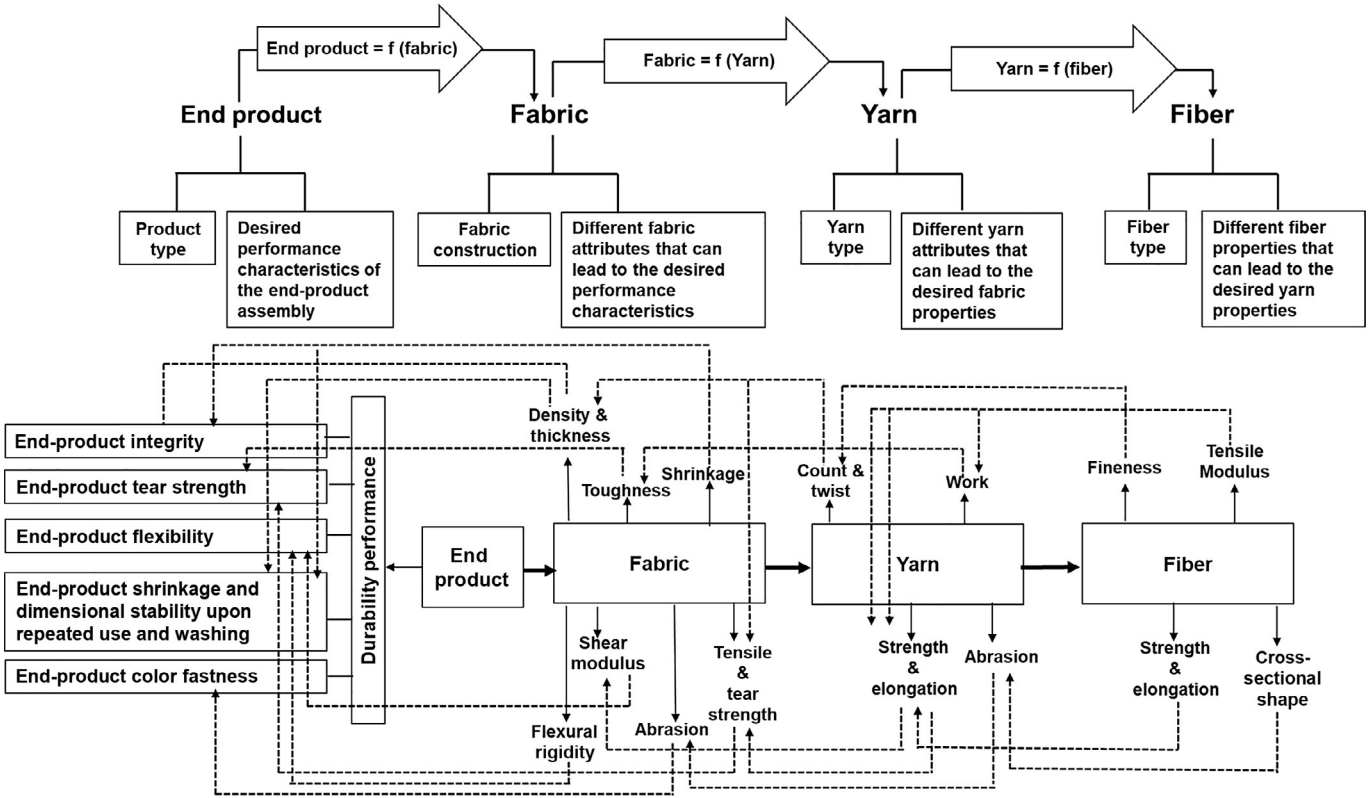


Fig. 12.1 Backward projection analysis: performance-attribute diagram of product durability.

should be transforming the value of fibers into an added-value to the end product. In the absence of scientific design approaches, the true value of fiber is often masked by its market price. As a result, cheap and low-quality fibers can result in a substantial loss of value of end products. On the other hand, expensive and high-quality fibers are often not guaranteed to produce value-added products. Therefore, a performance-attribute diagram should account for the cost of conversion from one fibrous structure to another and the value added to the end product as a result of using certain fibrous structures.

The primary challenge of implementing backward projection analysis is developing reliable relationships between the desired performance characteristic and relevant attributes. In a design project, these relationships essentially represent design-problem models that can be used to explore different effects and predict critical outcomes. In Chapter 5, examples of design-problem models intended for exploring neurophysiological and thermophysiological comfort were presented [8–17]. These models were developed by different scientists to explore the complex nature of the comfort phenomenon. Scientists commonly use two approaches of research: inductive reasoning or deductive reasoning. Inductive reasoning is based on using actual data produced from material testing for the sake of revealing trends or patterns that can be generalized into some form of universal models or theories. On the other hand, deductive reasoning begins with some facts for the purpose of deducing other facts, perhaps through experimental validation. In practice, inductive reasoning often yields models that are highly specific and applicable only to identical situations. On the other hand, deductive reasoning approaches are highly theoretical, and they often involve many speculative assumptions. In textile science, both approaches assume that the fiber-to-end product conversion system is ideally represented by a linear or a quasi-linear process, while the actual system is a complex nonlinear one. In addition, variability in fiber, yarn, and fabric properties is inevitable even within the same manufacturing process. These obstacles often result in using intermediate approaches in carrying out backward projection analysis in design engineering. It is more of an "abductive reasoning" approach in which the design project is initiated using an incomplete set of observations or preliminary information about the product constituents and then proceeds by finding the likeliest possible explanation for the available observations. Based on this explanation, hypotheses and educated guesses are made. This approach may not yield an optimum solution of the design problem, but it often represents the only option available in view of the lack of trackability and the high variability.

12.3 Typical attributes of fibrous assemblies

In the earlier sections, the differences between performance characteristics and related attributes were discussed. It was clearly pointed out that performance characteristics are described by responsive behavior to specific uses or certain levels of external stimuli (environmental or mechanical). On the other hand, material attributes can be tested using standard techniques. A discussion of what constitutes a performance

characteristic should therefore be made in reference to the specific product under consideration. In the following chapters of this book, examples of textile products will be discussed with a great deal of emphasis on their specific performance characteristics. In the following sections of this chapter, the focus will be on the main attributes of fibrous assemblies. These attributes can be divided into four main categories: (1) structural attributes, (2) mechanical attributes, (3) surface-related attributes, and (4) transfer attributes.

12.3.1 Structural attributes of fibrous assemblies

In most design projects of textile products, the primary focus is normally on fiber type. As discussed in Chapter 8, different fiber types can indeed yield different performance characteristics of end products. However, fibers are not represented in their raw forms in the end products; instead, they must be embedded into fibrous assemblies such as yarns and fabrics before an end product is made. The conversion of fibers into yarns and fabrics requires structural transition from a linear structure represented by a yarn to a two-dimensional or three-dimensional structure represented by a fabric. This transition is typically associated with a loss of integrity, which is often inevitable by virtue of the techniques used to make these structures. For example, the conversion of fibers into a yarn structure is inevitably associated with a loss in the relative contribution of fiber strength to yarn strength. In continuous-filament yarn, a maximum fiber-to-yarn strength efficiency can be obtained. In staple fiber yarns (e.g., ring-spun yarns, open-end spun yarns, and air-jet spun yarns), the fiber-to-yarn strength efficiency may range from 60% to 80% depending on the method of fiber consolidation in the yarn [18,19]. When yarns are converted into fabrics, the relative contribution of yarn attributes to the fabric will largely depend on the fabric structure used. Therefore, it is important to fully understand the structural features of the different elements constituting a textile product. As shown in Fig. 12.2, fibers can be converted into different yarn structures each of different unique attributes as discussed in Chapter 9. Yarns can also be converted into different fabric structures each of different unique attributes as discussed in Chapter 10. Modeling performance characteristics of textile end products must account for these structural features.

The conversion of fibers into a yarn must achieve two key design criteria: yarn integrity and yarn flexibility. The integrity of a yarn is maintained by accommodating certain number of fibers per yarn cross section and by using an appropriate binding mechanism of fibers. Fibers in a yarn are not tightly held together by a binding agent such as glue or cement; instead, they are typically held together using twisting or wrapping. These unique binding mechanisms yield flexible yarn structures. In practice, the number of fibers per yarn cross section is measured indirectly by yarn diameter, or yarn linear density (commonly known as yarn count in tex or English count). It can also be measured by yarn volumetric density (g/cm^3). Yarn twist is measured by the number of turns of twist per unit length (turns per inch or turns per cm) and the twist direction (S or Z). Yarn count and twist levels are commonly used as identity measures of spun yarns.

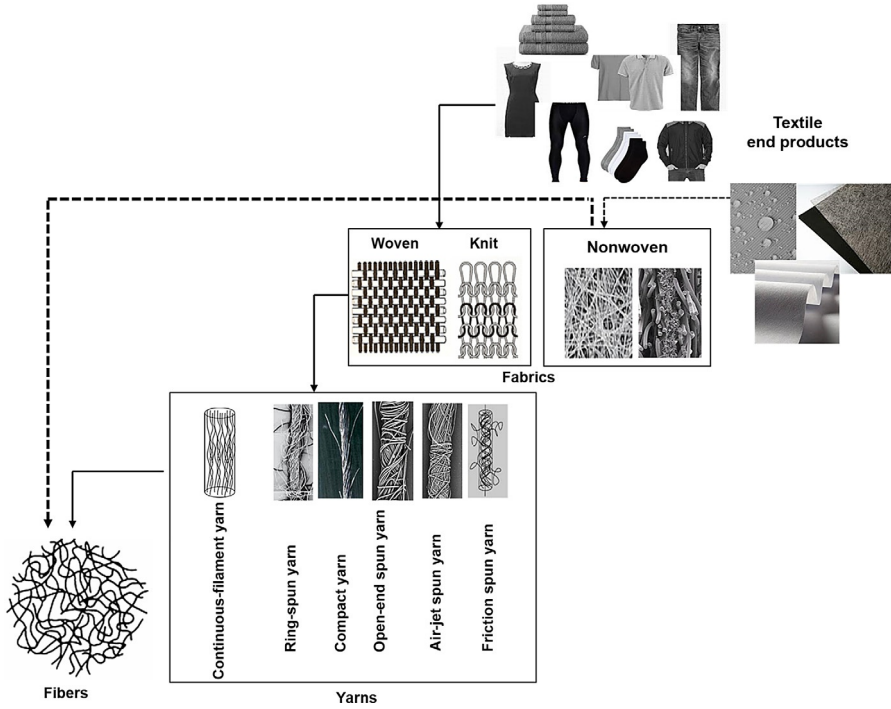


Fig. 12.2 Different material structures used in the design of textile products.

In the design of a fabric for a certain end product, it will be critical to understand the impacts of the structural attributes of yarn on fabric performance. A wide range of yarn count can be produced within a certain spinning system, but some spinning systems may be limited to certain ranges of yarn count [18,19]. Very fine yarns (above 50s English count, or below 12 tex) are typically more expensive than coarser yarns despite the fact that they require less number of fibers per cross section. This is because of the higher cost of manufacturing fine yarns and the need to use expensive fine and long fibers. In the spinning process, the finer the yarn, the slower the spinning process, and the lower the production rate. For these reasons, very fine yarns are used for high-end fashion fabrics that exhibit light, soft, and thin structures. Medium yarns (20s to 36s) are used for fabrics used in common apparel products, and coarse yarns (below 10s) are commonly used for thick fabrics such as denim and some working uniforms.

Different yarn types may require different levels of twist by virtue of their desired performance and end-use applications. Continuous filament yarns typically require no twist to impart integrity or strength. Nevertheless, small amount of twist (one or two turns per inch) may occasionally be inserted in this type of yarns merely to control the fibers and prevent them from splitting apart. Twist may also be inserted in continuous-filament yarns to avoid ballooning out as a result of accumulating electrical charges.

In some situations, high amount of twist may be inserted in continuous-filament yarns to break up luster of the yarn or to impart some other effect or fancy attributes. However, high twist levels in these yarns can result in deterioration of their strength as discussed in Chapter 9.

The combination of twist level and twist direction represents a key parameter in the design of spun yarns. Different spun yarns may require different levels of twist. For example, warp yarns used for weaving normally have higher twist levels than weft yarns because of the higher strength required in these yarns. Knit yarns typically have lower twist than woven yarns to provide better softness. Some spun yarns may exhibit very low twist to produce lofty structures. This is typically the case of weft yarns that are to be napped by teasing out the ends of the staple fibers and create soft, fuzzy surfaces. Other spun yarns may exhibit very high twist levels to meet their application needs. These include voile and crepe yarns. Voile yarns are typically made of high twist to create an intentional stiff feel in the fabric by plying yarns in the same twist direction as the single yarns to increase the total twist. This provides a lightweight stiff furnishing or curtain fabrics that can be made from 100% cotton or cotton blends with linen or polyester. Crepe yarns, also known as unbalanced yarns, have the highest levels of twist. The idea is to create a yarn of high liveliness desired in some apparel products.

The importance of twist direction is realized when two single yarns are twisted to form a ply yarn. Ply twist may be Z on Z or S on Z depending on appearance and strength requirements of the ply yarn. When the yarn is woven or knitted into a fabric, the direction of twist influences the appearance of fabric. When a cloth is woven with the warp threads in alternate bands of S and Z twist, a subdued stripe effect is observed in the finished cloth due to the difference in the way the incident light is reflected from the two sets of yarns [20,21]. In twill fabric, the direction of twist in the yarn largely determines the predominance of twill effect. For right-handed twill, the best contrasting effect will be obtained when a yarn with Z twist is used; on the other hand, a left-handed twist will produce a fabric having a flat appearance. In some cases, yarns with opposite twist directions are used to produce special surface texture effects in crepe fabrics. Twist direction will also have a great influence on fabric stability, which may be described by the amount of skew or "torque" in the fabric. This problem often exists in cotton single-jersey knit where knitted wales and courses are angularly displaced from the ideal perpendicular angle. One of the solutions to solve this problem is to coordinate the direction of twist with the direction of machine rotation [21]. With other factors being similar, yarn of Z twist is found to give less skew with machines rotating counterclockwise. Fabrics coming off the needles of a counterclockwise rotating machine have courses with left-hand skew, and yarns with Z twist yield right-hand wale skew. Thus, the two effects offset each other to yield less net skew. Clockwise rotating machines yield less skew with S twist.

The conversion of yarn into a fabric is associated with a significant structural transition of the fiber assembly. Indeed, it is this transition that determines what end product can be produced from a certain fabric structure. As discussed in Chapter 10, woven fabrics are characterized by many structural parameters that collectively reflect their performance criteria. These parameters include [20–22] fabric count, fabric width,

fabric thickness, fabric weight or area density, and fabric crimp. Knit fabrics are also characterized by many structural parameters including [23–27] fabric count, stitch density, shape factor, tightness factor, weight or area density, linear density, and fabric width. Nonwoven fabrics are characterized by key structural parameters including [28–32]: fabric thickness, fabric weight or area density, and fiber alignment and orientation.

The basic structural attributes discussed earlier can be measured using standard techniques. Other structural attributes that can have direct impacts on the performance of traditional fibrous products include cover factor, fabric specific volume, and fiber fraction. These are derivatives of the basic attributes, and they are normally estimated, not measured. The term cover factor was introduced earlier in Chapter 10. It is an index of the area covered with fibers with respect to that covered with air in the fabric plane. Fabric specific volume is an index of bulkiness or yarn compactness in the fabric in a three-dimension geometry expressed by the following equation [4,5]:

$$\nu_{fabric} = \frac{t}{W}\ \mathrm{m}^3/\mathrm{g}$$

where t is fabric thickness (m) and W is fabric weigh (g/m^2). Given the fact that fabric thickness is highly sensitive to the pressure applied on the fabric during testing, it is important to specify whether the fabric thickness was measured under a relaxed and natural state or under some levels of lateral pressure. Knit structures are generally characterized by significantly higher specific volume (more fluffiness) than woven fabrics. Typical specific volume values of knit structures used in apparel products may range from 3.0 to 6 cm^3/g. Woven fabrics used for apparel products will typically exhibit specific volume values of less than 3.5 cm^3/g.

The structure of a fiber assembly (yarn or fabric) will consist of two main components: fiber and air. The coexistence of these two components is critical for a wide range of performance characteristics. Measuring the volume fraction of either component requires careful experimental procedures as separating air from fiber in a fibrous structure is a very difficult task. Instead, fiber fraction is typically estimated using the following equation [4,5]:

$$\text{Fiber fraction}, FF\ (\%) = \frac{\varepsilon v_f}{v_{fab}} \times 100$$

where v_f is fiber specific volume (e.g., about 0.65 cm^3/g for cotton, and 0.75 cm^3/g for polyester), v_{fab} is the specific volume of fabric, and ε is a correction factor accounting for yarn compactness, and yarn packing fraction. The percent of fiber fraction in a fiber assembly will largely vary depending on the fabric construction. Values of fiber fraction for woven fabrics may range from 20% to 30% in most apparel products. Knit structures used in apparel products will typically exhibit lower fiber fraction (typically, 10%–20%).

From a design perspective, the structural attributes of fabric are directly transformed into performance characteristics of end products. This point will be clearly

illustrated in the following chapters of this book using specific examples of textiles. In the design of traditional textiles products, the levels of structural attributes should be optimized in view of required levels of key performance characteristics such as durability and comfort. In general, heavier, thicker, and denser fabrics (e.g., apparel bottoms, working overalls, military uniforms, curtains, and furnishing products) are likely to be stronger and stiffer than lighter, thinner, and open fabrics (e.g., apparel tops, underwear, some sportswear, and some bed sheets). Comfort being a twofold performance characteristic (tactile and thermal) requires more careful evaluation of the effects of fabric structural attributes. For tactile comfort, a thinner, lighter, and more open fabric may be appropriate. This is largely true with woven fabrics in which thicker fabrics are also heavier and denser than thinner fabrics (e.g., plain and satin). For knit fabrics, thickness and weight can be independent, especially when one goes across different knit patterns. For example, an interlock knit structure, which is thicker than pique fabric, can also be lighter despite being denser. This trade-off can be achieved using finer yarns in the interlock pattern. When softness under lateral compression (hand or finger pressing against fabric surface) is considered, knit fabrics are likely to offer softer structure by virtue of their high thickness and low-density combinations in comparison with those of woven fabrics. When thermal comfort is of concern, fabric thickness and fabric density will represent key structural attributes due to their effects on thermal insulation by virtue of entrapping still air in the internal structure.

12.3.2 Mechanical attributes

Textile products may be subjected to different modes of deformation including tension, compression, bursting, tear, bending, shear, friction, and abrasion. Table 12.1 provides a list of common mechanical attributes describing these modes of deformation. Details on these attributes and their testing methods can be found in many literatures [1,5,7,18,21]. These modes of deformation can influence fabric durability over time. Traditional textiles are typically subjected to these modes of deformation as a result of repeated wear, washing, and drying. In some situations, deformation imposed by high physical activities and harsh working conditions can accelerate the deterioration of garment. Technical textiles may be subjected to severer levels of deformation depending on the application as will be discussed in Chapters 14 and 15. In most applications, the tensile behavior of fabric represents the most critical design parameter. This is particularly true for woven fabrics. In these applications, it will be important to develop a design-problem model of fabric tensile behavior. One of the common expressions of tensile behavior of textile fabrics is the following one, describing fabric tenacity [5]:

$$\text{Tenacity} = \frac{\text{Tensile breaking load}\,(g_f)}{\text{Area density}\left(\frac{g}{m^2}\right)}\,(g_f/\text{tex})$$

From a design perspective, the numerator of the earlier relationship describes pure mechanical attributes of the fibers and yarns used to make the fabric. This means that

Table 12.1 Mechanical attributes of fiber assemblies [1,5,7,18,21].

Mechanical parameter	Description	Examples of units used
Tensile strength (F)	The force required to rupture a fiber, yarn, or fabric under applied tensile stress	g_f, lb_f, N, or cN
Tensile stress (σ)	σ = Force/Area = F/A	g_f/mm^2, PSI, kg_f/m^2
Specific stress (σ_s)	Force per unit linear or area density σ_s = F/tex, or F/denier (tex = g/km, denier = g/9 km)	g_f/tex, g_f/denier, or cN/tex
Strain (%)	$\varepsilon = (\Delta l/l_o)100$ = increase in length under tension/original length	Percent (%)
Stress-strain curve (σ-ε)	The curve describing the progressive changes in material deformation under external stress	
Yield stress	The stress at which the material begins to suffer irrecoverable deformation	g_f/tex, g_f/denier cN/tex
Work of rupture (toughness)	The measure of the ability of material to withstand sudden stresses, expressed by the total area under the stress-strain curve	g_f/tex, g_f/denier cN/tex
Elastic recovery	The extent of recovery upon removal of external stress as expressed by the elastic recovery (%)-stress curve	
Fabric tear strength	The force required to rupture a fabric when lateral (sideways) pulling force is applied at a cut or hole in the fabric	g_f, lb_f, N, or cN
Bursting strength	The force required to rupture or create a hole in a fabric when a lateral force (perpendicular to the fabric plane) is applied on a mounted specimen	lb_f or kg_f
Stiffness	The resistance of a fibrous structure to tension, bending, or shear Under tension: elastic modulus (E) Under bending: flexural rigidity (FR) Under torsion: torsional rigidity (TR)	E = cN/tex, gf/denier FR = gwt. squared-cm TR = gwt. squared-cm
Abrasion resistance	The resistance to wearing away of any part of the fabric by rubbing against another surface	Number of cycles to rupture

using stronger fibers is likely to produce stronger fabric for a given yarn structure. On the other hand, using different yarn structures is likely to result in different levels of fabric tensile strength due to the fact that different yarn structures will yield different levels of fiber-to-yarn strength efficiency as discussed earlier. The denominator of the earlier equation, or fabric area density, is purely related to fabric structure. A larger area density may result from using coarser yarns for a given fabric construction (i.e., fabric width) or from using finer yarns at high fabric density (threads per inch).

A larger area density may also be produced by making a compound fabric of multiple layers. Accounting for these parameters in a theoretical model will be extremely difficult given the multiplicity of variables and their inevitable interactions. For this reason, previous theoretical models were largely idealized, and they were associated with many assumptions [5]. Nevertheless, those models were exploratory enough to shed a great deal of light on many of the key structural parameters influencing fabric strength. In design projects involving fabric strength, the alternative approach should be to develop empirical models in which key related parameters are considered within their plausible ranges. Key variable in this relationship should include fiber-to-yarn strength efficiency, yarn structural attributes such as count and twist level, and fabric structural attributes such as fabric density and fabric thickness.

The general form of such relationship should be as follows:

$$\text{Fabric tenacity} = f\{\text{fiber} - \text{to} - \text{yarn strength efficiency, yarn count,}$$
$$\text{twist, fabric density, fabric thickness, etc.}\}$$

Note that the variables considered in the earlier general function are all design related and they can be optimized using well-established techniques. The fiber-to-yarn strength efficiency will be largely determined by the type of fiber used and the spinning method; yarn structure parameters such as count and twist can be altered within a particular spinning system or using different spinning systems when one system exceeds its limits; finally, fabric structural attributes can be altered by manipulating the yarn structural parameters for a particular fabric construction or by using different fabric constructions. Currently, these design options are implemented in the textile industry solely based on experience and trial and error. For example, a combination of cotton coarse yarn (6s to 10s) and a 3/1 twill weave in denim fabric may yield a fabric tenacity of 10–12 g_f/tex, while a cotton plain weave made from medium or fine yarns may yield a fabric tenacity of 5–7 g_f/tex. Utilizing design-problem models will certainly result in better optimum levels of fabric tenacity, possibly at lower material cost.

When knit fabrics are used in textile products, tensile resistance becomes less significant, and elongation or fabric stretch becomes the dominating performance characteristics of these products. For example, a single-jersey fabric may exhibit an elongation of up to 90% compared with only 5%–15% of a plain weave fabric. This may mean a substantial difference in the corresponding fabric flexibility as determined by Young's modulus from as low as 2 g_f/tex for single jersey to more than 10 g_f/tex for plain weave. Most knit fabrics are stretchable and flexible under tension by virtue of their open and low dense construction. On the other hand, woven fabrics are stronger by virtue of their close and dense structure. Within the knit fabric category, different fabric construction will yield different elongation and flexibility levels provided that the fabrics are made from the same fiber type and yarn structure. A design-problem model of knit fabric aiming at optimizing its mechanical properties may be simpler than that used for woven fabric since it will be primarily related to structural attributes.

Another key mechanical attribute of fabrics is fabric drape, which describes the way a fabric hangs under its own weight. In general, the draping performance expected from a fabric will differ depending on its end use. Therefore, a given value for drape cannot be classified as either good or bad. For example, in the context of hand and comfort, the importance of drape stems from the need for garments that can easily follow the body contours. Knitted fabrics are relatively floppy, and garments made from them will tend to follow the body contours. Many woven fabrics are relatively stiff when compared with knitted fabrics so that they are used in tailored clothing where the fabric hangs away from the body and disguises its contours. Accordingly, one should expect distinguished drape behavior between knit and woven fabrics. Measurements of a fabric's drape should be capable of providing quantitative values and indications of the ability to hang in graceful curves.

Fabric drape is measured by the so-called drape coefficient. This is typically obtained by using a circular specimen about 10-in. diameter, supported on a circular disk about 5-in. diameter to allow the unsupported area drapes over the edge. Since fabrics will typically assume some folded (double-curvature) configuration, the shape of the projected area will not be circular, and a drape coefficient, C_d, is obtained from the following equation [4,5]:

$$C_d = \frac{A_s - A_d}{A_D - A_d}$$

The parameters presented in the earlier equation are illustrated in Fig. 12.3 with typical values of fabric drape for different fabric structures obtained from a previous study [33] by the author that aimed at developing a design-oriented fabric comfort model. The idea of the earlier equation is to determine the ratio between the draped shape of fabric (A_s) and the undraped shape (or the circular shape, A_D). Accordingly, the smaller the drape coefficient, the higher the propensity to drape. As illustrated in Fig. 12.3, knit fabrics will generally exhibit lower drape coefficient or higher propensity to drape than woven fabrics. Among the knit fabrics, single jersey exhibited the highest propensity to drape (lowest drape coefficient), and interlock exhibited the lowest propensity to drape (highest drape coefficient). Among the woven fabrics, plain weave exhibited the highest propensity to drape (lowest drape coefficient), and twill exhibited the lowest propensity to drape (highest drape coefficient). Key design factors that can influence fabric drape will include fiber stiffness, yarn flexural rigidity, fabric thickness, fabric weight, fabric count, and yarn count.

12.3.3 Surface-related attributes

Surface-related attributes of fiber assemblies have been studied extensively by many textile research scientists [13,14,33–37]. From a design perspective, many parameters can contribute to the surface behavior of fabric. Fig. 12.4 illustrates some of these parameters. At the fiber level, important surface-related attributes include fiber birefringence, surface area, cross-sectional shape, surface roughness, fiber crimp, and

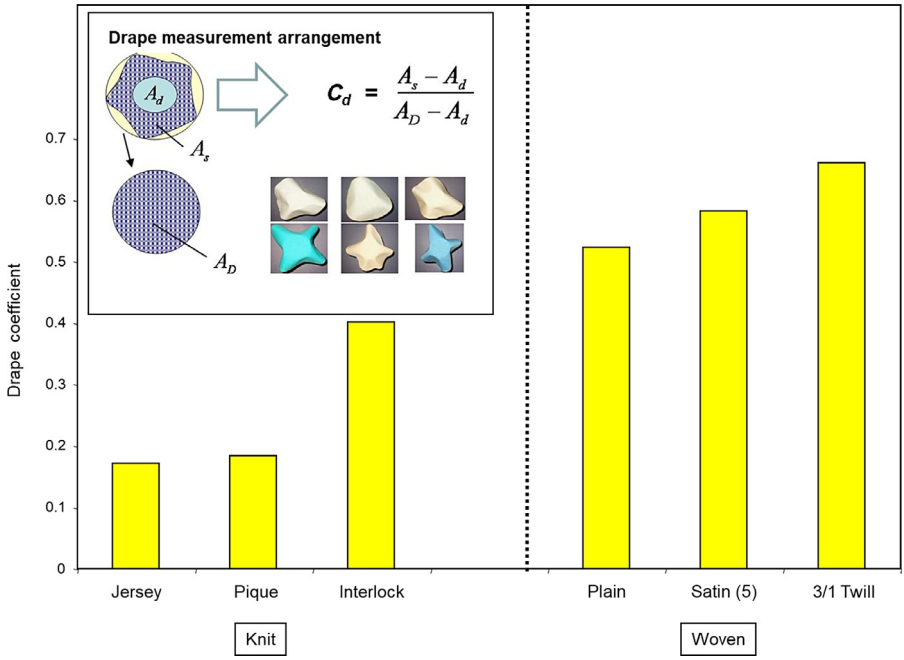


Fig. 12.3 Drape coefficient of different 100% cotton fabrics [33].

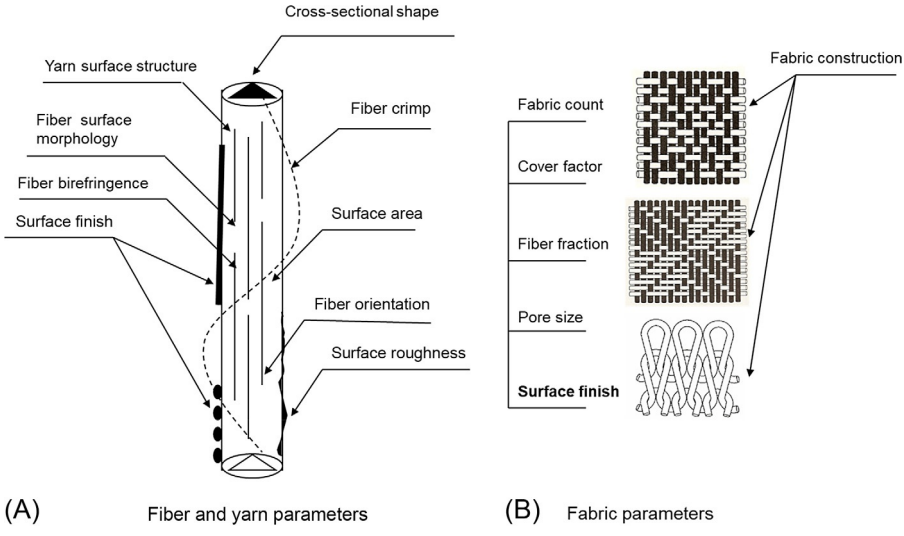


Fig. 12.4 Design parameters influencing the surface characteristics of fibrous assemblies.

surface molecular orientation. At the yarn level, yarn type and its associated structural features (e.g., fiber arrangement, fiber mobility, and fiber cohesion) can influence the surface behavior of yarn. At the fabric level, fabric construction and structural features (fabric count, fiber fraction, thickness, etc.) can all contribute to the surface performance of fabric. In relation to performance characteristics of textile products, the importance of surface attributes stems from the following aspects:

(1) In traditional textiles, the surface of textile products reflects an integral aesthetic aspect of most apparel and fashion products. It provides the first impression about the quality of garment either through the color and surface pattern or through the initial touch and feel of fabric.
(2) Surface characteristics represent key design parameters in providing tactile comfort, particularly when fabric comes into contact with human skin.
(3) Surface characteristics represent key design parameters in providing thermal comfort as surface roughness plays an important role in both heat and moisture transfer.
(4) Surface roughness represents a key design parameter in many technical textiles particularly when fabrics come into contact with other solid surfaces.
(5) The surface of many textiles is likely to undergo changes over time depending on the use frequency of the product. Soft surface can become rougher over time (e.g., towels), and rough surfaces can become softer over time due to wear-out effects.

In practice, optimization of the surface characteristics of textile fabrics begins with the selection of fiber type as different fiber types exhibit different surface characteristics. Comparisons of surface characteristics of different fibers are outside the scope of this book, but they can be found in many literatures [33–37]. In Chapter 11, several methods of surface finish treatments were described. For fabrics made from synthetic fibers, different surface modifications can be made during fiber production or during fabric finishing. These include hydrolysis (alkaline and enzymatic), surface grafting, plasma, and excimer ultraviolet (UV) laser. One category of surface treatments applied to cellulosic fibers is the so-called durable-press treatments. This includes treatments to impart wrinkle resistance, permanent creases, shrinkage resistance, and smooth drying properties. These are essentially dimensional stabilization treatments that can be applied to yarns, fabrics, or entire garments made of cotton or its blends with polyester. They are essentially based on using cross-linking agents that react with hydroxyl groups of cellulose in the presence of heat and catalysts to form covalent cross-links between adjacent cellulose molecular chains. Surface treatments can also be made using nanoparticles to induce special effects such as hydrophobicity. Coating of textiles is another form of surface treatment that can be used for many purposes including protection. Many smart textiles are now produced with the capability of sensing environmental effects (e.g., thermal, radiation, or chemical) and respond to them by blocking their effects from harming the human body, while not interfering with moisture and air interchange through it to provide comfort. Other types of surface treatments are used to impart smart, adaptive properties for protective systems.

One of the challenges associated with the design for surface performance of textiles stems from the need to understand the nature of fiber-to-fiber contact and fiber-to-solid contact. Based on the author's experience in this specific area, the surface behavior of fibers and fiber assembles is fundamentally different from

other solid materials. For example, one of the common measures of surface behavior is the coefficient of friction, μ, obtained from the classical law of friction, $F = \mu N$ (where F is the frictional force and N is the lateral force). This law typically assumes that the coefficient of friction, μ, is constant at all levels of lateral forces and is independent of the area of contact. This assumption has been questioned in previous studies [38–40], and it was generally found to be inappropriate for materials deforming elastically or viscoelastically under lateral pressure. Fibers typically deform viscoelastically under lateral pressure. When the fibers are formed into fibrous structures or assemblies, the assumption of viscoelastic deformation continues to hold. An alternative relationship found empirically by many investigators [38–45] is in the following form: $F = aN^n$, where a and n are called the friction indexes. Note that at $n = 1$, this equation becomes identical with the classical friction equation, $F = \mu N$. The nature of the two friction indexes in this equation was studied in detail by the author of this book, and the reader is encouraged to refer to the book edited by Professor B.S. Gupta [34,35] to obtain full details on the subject. In the context of design, the index a largely resembles the classic coefficient of friction, μ, but it also depends on surface roughness and the true area of contact. The parameter, n, on the other hand depends on the deformational behavior of the fiber assembly at the points of contact. Softer and easily deformed assemblies are likely to yield lower n values. In addition, external conditions such as sliding speed, temperature, and moisture on the surface will influence both indexes in a complex manner. The theoretical models developed by the author and other scientists in the field can be very useful in exploring the nature of fiber friction. The challenge, however, will be in transforming these models into design-problem models for the sake of optimizing surface performance characteristics. This challenge can only be met through cooperative efforts between textile scientist and textile engineers.

12.3.4 Transfer attributes

Transfer attributes are those characterizing fluid and heat transfer through fabrics. These are expected to be directly influenced by structural attributes such as fabric construction, fabric specific volume, and fiber fraction. Another critical parameter that can play a vital role in relation to transfer properties is the pore size of fabric. Fabric pores are the minute openings in the fabric structure. The existence of pores in the fabric structure is a natural consequence of the method of fabric formation. Pores can be controlled in size and number through many design options including fabric construction, geometrical features within a given fabric construction, yarn structure, fiber dimensional properties, and fabric finish.

Pore size and pore size distribution are essential parameters in determining the performance of many traditional and technical textile products. For instance, fabric wicking, one of the key moisture transfer phenomena, is essentially a capillarity mechanism in which wicking can be visualized as a spontaneous displacement of a fiber-air interface with a fiber-liquid interface in a capillary system. In this regard, the height of the fluid column, h, is a critical parameter characterizing the capillary effect of fibrous assemblies [46,47]. This height is inversely related to the pore diameter. The porous structure of fabric is also a key factor in providing flexibility as the more porous structure is likely to produce a more flexible fabric.

The fact that the pores in fibrous assemblies are not typically uniform in size necessitates the analysis of the shape, size, and frequency of pores in the fabric structure [48,49]. One approach to determine pore size is by determining the relative amount of air or fluid flow through the fabric gaps [50,51]. This method is very useful in simulating the effect of pores in critical phenomena such as filtration and moisture or air transfer. However, it provides insufficient exploration of the true porous structure (size and distribution). Image analysis represents another reliable approach of determining pore size and shape.

In addition to pore size, other transfer attributes include air permeability and thermal resistance. The term air permeability refers to the measured volume of air in cubic feet that flows through 1 square foot of cloth in 1 min at a given pressure. In the context of apparel comfort, air flow through fabric is critical in two aspects: breathability and thermal insulation. A typical apparel fabric should have the capability of transferring air for ventilation and freshening purposes. In connection with thermal insulation, air is the most insulative material (thermal conductivity of air is 0.025 W/mK). This means that for fabric to exhibit good thermal insulation, it should have the ability to entrap air in its internal structure. A fabric that has low resistance to air flow (high air permeability) is likely to be a conductive fabric.

The heat flow through fabrics can be described using many measures including thermal conductivity, thermal resistivity, thermal absorptivity, and thermal diffusivity. The general heat flow equation is as follows [52–54]:

$$Q = \lambda\left(\frac{T_1 - T_0}{h}\right)$$

where Q is heat flow (W/m^2), λ is thermal conductivity (W/mK), T_1 is heat source temperature (K), T_o is fabric temperature (K), and h is fabric thickness (m).

As indicated in Chapter 8, thermal conductivity is a material property that expresses the heat flux Q (W/m^2) that will flow through the material if a certain temperature gradient ($T_1 - T_o$) exists over the material. In other words, the thermal conductivity, λ, is the quantity of heat transmitted, due to unit temperature gradient, in unit time under steady conditions in a direction normal to a surface of unit area, when the heat transfer is dependent only on the temperature gradient. Since fabric consists of both fibers and air, the thermal conductivity of a fabric structure should be determined by the following equation [52]:

$$\text{Fabric thermal conductivity} = \lambda_{air}(1 - f) + f\lambda_{fiber}$$

where f is the fraction by volume of the fabric taken by fiber.

Another measure closely related to thermal conductivity is thermal resistivity, which is a measure of insulation of material. It is defined as the temperature difference between the two faces of the sample divided by the heat flux [52]:

$$R_t = \frac{h_t}{\lambda}$$

where R_t is thermal resistance (m^2K/W), h_t is total thickness of the fabric (m), and λ is thermal conductivity (W/mK).

It is important to point out that unlike other homogenous solid structures, fibrous structures typically exhibit a complex thermal behavior. In the case of homogenous solid material and for a given material type, thermal resistance is predominantly influenced by the thickness of material. Accordingly, if the material is of low thermal conductivity, the thicker the material, the more insulative it will be. In the case of fibrous structures, thicker material does not necessarily mean higher thermal resistance. This is because a fiber structure typically consists of fibers and air, and in apparel fabrics, the air content can be substantially greater than the fiber content. However, the actual existence of air depends largely on the ability of fabric structure to entrap the air inside. The more air entrapped inside the fabric structure or the lower the propensity of air to escape the fabric, the higher the thermal insulation or the lower the chance for human body to lose heat by air convection.

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Performance characteristics of traditional textiles: Denim and sportswear products

13

13.1 Denim products

Among all traditional fibrous products, no other product in history has been more widely accepted and more widely used by people of all cultures, genders, ages, and origins than denim fabric, which obtains its authenticity from interweaving an indigo (blue) warp yarn and white filling threads in a twill structure. The word denim is an Americanization of the French name "serge de Nimes," a fabric which originated in Nimes, France, during the Middle Ages. The brief term "denim" was adopted by the Webster's dictionary as the English version of denim in 1864. Other related terms are jeans, Dungarees, or Levi's. Jeans came from cotton trousers that were worn by Italian sailors from Genoa; the term is again French, as the French call Genoa and the people who live there "Genes." Dungarees came from the word "dungrí" in Hindi, and it means coarse cloth. This term is typically used to refer to blue denim fabric or to trousers made from them. The term Levi refers to Levi Strauss, one of the most famous brands in the denim business [1, 2].

The story of jeans or blue jeans reflects a true example of how the user of a product can indeed drive the product development process. The initial development of jeans was in two styles: indigo blue and brown cotton "duck," which was a heavy plain weave fabric. Cotton duck being heavy and uncomfortable was eventually terminated and replaced by denim fabric. In 1873, two American immigrants Jacob Davis and Levi Strauss patented the so-called waist overalls or work pants. Jacob Davis, a tailor, was one of Levi's many customers who regularly purchased bolts of cloth from the wholesale house of Levi Strauss & Co. Some of Jacob's customers complained about the weakness of pockets of the pants and their continuous ripping. In an attempt to strengthen the men's trousers, Jacob came up with the idea of putting metal rivets at the pocket corners and at the base of the button fly. This development was an instant success with Jacob's customers. To protect the idea, Jacob patented it with his business partner Levi Strauss on May 20, 1873 (US Patent and Trademark, patent no. 139.121). This was the birthday of blue jeans. In a latter development, metal rivets were eventually replaced by reinforced stitching.

Today, denim is a multibillion-dollar business and a multicategory apparel segment. Indeed, one can find denim products at every retail channel and at price points ranging from under 10 dollars to hundreds or thousands of dollars. Denim fabric can be made into a wide range of fibrous products including pants, skirts, shirts, shorts, jackets, hats, bags, upholstery, wall coverings, and bedsheets. As a result, denim fabrics can be made in many weights (as determined by yarn count and fabric density, warp per inch, and

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filling per inch). A typical range of denim fabric weight is from 5 to 16 oz/yd^2. Light denim will be suitable for dresses or shirts where drape, softness, and flexibility are required. Heavy denims in the range from 10 to 15 oz/yd^2 are typically used for blue jeans pants and skirts. Most denim fabric is made from cotton fibers, but a considerable amount is made from cotton blended with other fibers at different blend ratios. Typically, most yarns used for denim fabric are open-end or rotor-spun yarns, but a significant amount is made from ring-spun or compact yarns. A combination of ring-spun and open-end spun yarns may also be used in the same denim fabric.

Denim fabric is commonly treated with a variety of finish to enhance its performance. Unlike most traditional woven fabrics, denim fabric finish begins in the yarn form. The warp yarn is dyed prior to weaving by removing individual strands of yarn from yarn packages during the warping process and prior to being gathered into a rope form suitable for dyeing. In the dye range, the yarn rope typically goes through scour/sulfur treatment, wash boxes, and indigo dye vats, over a "skiing" device (to allow oxidation to occur), through additional wash boxes, and over drying cans and then is coiled into tubs, which are transferred to a beaming process. This process separates the dyed yarn into individual parallel strands and winds them onto a large section beam in preparation for sizing or slashing, which involves coating the yarn with a starch/wax solution and winding the yarn onto a loom beam. Weft yarns join the warp yarns in the weaving process.

In the fabric form, denim is commonly treated with a variety of finish depending on the performance characteristics required. Some fabric may be brushed and singed prior to chemical treatment. During finishing, the fabric is normally pulled to a predetermined width, skewed, dried, and rolled for the next process. Denim fabric may be categorized as dry denim or washed denim. Most denim fabric is washed after being crafted into a clothing article to make it softer and to eliminate any shrinkage, which could cause an item to not fit after washing by the wearer. Prewashing will completely remove the size material from the warp yarns, resulting in softer fabric. Following washing, some denim is treated with abrasive or deformation applications to create a worn-in appearance of the denim garment, which is a desirable feature of most fashionable denim. Dry denim does not go through this operation. Instead, it is left to the wearer to apply repeated washing during the normal use until it exhibits a natural color fade.

13.1.1 Development of denim products

The basic tasks of product development were discussed in Chapter 3 and demonstrated by the subsequent steps of Fig. 3.1. As clearly indicated in Chapters 3 and 4, design conceptualization represents the foundation of any design process. This is the process of generating ideas for an optimum solution to the design problem. Fig. 4.3 of Chapter 4 illustrated the basic steps toward design conceptualization. The initial step is to initiate an idea of a denim product and establish objective justifications for the idea in view of key criteria such as consumer-added value, potential users, producer-added value, and regulations and liability. In the case of denim product development, this justification may represent a difficult task as the market is almost

saturated with numerous denim products from the basic rugged denim to many high-end fashionable products. In recent years, many new ideas were introduced in the denim industry that followed different directions of development. Examples of these ideas are as follows [3–8]:

I. **High-performance denim**: This development has resulted in a shift from the domination of 100% cotton fibers in denim products to the utilization of many other fiber types including synthetic fibers, linen, and hemp for the sake of producing high-durability denim products particularly with respect to tensile and abrasion resistance. For example, high-performance denims were designed to overcome the so-called crotch blowout, a common complaint for denim wearers who ride bicycles on regular basis. These denims use specialty durable fibers such as Cordura, Kevlar, and Dyneema spun with cotton. The idea of producing high-performance denim will result in a more sustainable denim by virtue of extending the lifetime of a denim product.
II. **Sustainable denim**: Other ideas toward sustainability include the use of sustainably produced fibers such as Tencel and MicroModal fibers and recycled fibers as discussed in Chapter 6. Another sustainable development is the transition from stonewashed denim to more energy-efficient and environmentally friendly methods such as enzyme treatment, mechanical abrasion, ozone fading, water jet fading, and laser treatment. Furthermore, new ideas were based on a transition from the traditional indigo dyeing (the most water and chemical intensive process of denim manufacturing) to technologies that lower water consumption and create recyclable discharge. The challenge of such development is to maintain the features of a century-old process using the oldest dye in the world without corrupting the inherent character of indigo but at the same time significantly reducing the environmental impact of indigo dyeing. Ideas in this direction include using prereduced indigo dyeing instead of powder indigo (e.g., the Crystal Clear dyeing technique, developed by DyStar and Artistic Milliners in collaboration with G-Star and produced at Saitex), which saves significant amounts of water and uses 70% less chemicals, and it is salt free. Another approach is the use of nitrogen dyeing, which slows down oxidation and accelerates the dyestuff's penetration into yarns (e.g., Candiani's N-Denim). Foaming and spray dyeing also save considerable amounts of water.
III. **Stretch denim**: This development was based on using synthetic elastane fibers such as Lycra fiber that can stretch up to six times its length and return to its original state several times. This idea was promoted by the problem of lack of recovery and sagginess in older jeans after a few wears. Stretch yarn can be unidirectional or bidirectional in both weft and warp (e.g., bistretch denim).
IV. **Knit denim for comfort**: The idea of producing denim products from knit fabric was totally inconceivable few years ago. Now, new ideas are under research to produce denim effect using knit fabrics produced on single-jersey circular knitting machine that can create denim effect with knit and tuck loop separately [7]. Some research work revealed that denim effect on knitted fabric could be made from three types of technologies [8]: float plated technology, thread fleece, and interlock plaited jacquard. The idea of producing knit denim is primarily based on the known comfort-related advantages offered by knit products in comparison with woven products (i.e., free body movement and higher stretch). In addition, knit denim provides higher wrinkle resistance and better air permeability. These new innovations should be monitored closely in the next few years as they can result in a radical change in the denim business due to the cost advantages of producing knit fabric in comparison with woven fabrics and the possibility of meeting optimum trade-off between durability and comfort in denim design.

V. **Smart denim**: Being one of the most popular apparel products in the world, it was inevitable that denim products will enter the smart fashion business in a big way. In recent years, many commercial products were introduced to the market based on smart-denim product ideas. For example, a joint effort between the US jeans maker Levi Strauss and Google under the so-called Project Jacquard was initiated in 2015. The idea was to weave touch-sensitive fabric into everyday clothing. This allows a portion of the clothing (in the case of a jacket, the left cuff) to take touch inputs from a person's hand and translate them into input controls for your smartphone, with the help of a Bluetooth-powered dongle stored in the cuff. Those controls include music playback and some simple navigation pings within Google Maps. Other examples include waterproof jacket with sunscreen bands and a cable in the pocket to recharge a phone, jeans that keep human body temperature stable, moisture-wicking shirts and trousers and clothing that can track motion, heart rate, and body temperature.

Once a product idea is clearly justified, the design problem should be defined. As discussed in Chapter 4, a design problem represents the primary obstacle facing the design process or hindering a desirable optimum solution. In a broad sense, a design problem may be initiated by establishing a general or broad definition of the proposed product. Examples of this definition are as follows:

- Highly durable to moderately comfortable denim
- Highly comfortable to moderately durable denim
- Moisture-management denim

A broad definition should then be followed by a more specific definition of the design problem in which precise objectives and goals are stated, technical terms are defined, limitations and constraints are documented, probabilistic outcomes are discussed, and evaluation criteria are perceived. For example, when moisture management is the broad definition, a specific definition may be stated in terms of the exact objectives, say "a denim fabric that can provide cooling effects and sweat wicking in hot environment." This may be associated with options of fiber types (e.g., hydrophobic and hydrophilic), yarn structure (e.g., twist levels, yarn compactness, etc.), and special finish treatments. Probabilistic outcomes involve key issues stated in "what if" formats such as "what if the garment is worn in cold environment?" Finally, any design problem should be associated with criteria that will eventually be used to judge whether the problem has been solved and whether the solution was indeed optimal.

Following the justification and problem definition tasks, information should be gathered to complete the design conceptualization. Examples of information are those related to existing relationships between performance characteristics and potential attributes, specific scientific tools required to perform the design analysis, and other information that may require some experimental trials. Ultimately, design conceptualization should lead to a reliable answer to the question of whether the current state of the art warrants further efforts with potential added success. A positive answer to this key question represents the "go ahead" for generating ideas for optimum solutions to the design problem and for formulating the design concept.

The next task of product development is to determine and define product performance characteristics using appropriate performance-attribute diagram as discussed in Chapter 12. The two main performance characteristics of denim products are

durability and comfort. Durability represents the most anticipated characteristic of denim products by virtue of the expected wear time and the use frequency of these products. Indeed, the first perception about denim products among all consumers is durability and sturdiness. For this reason, traditional denim is produced in a manner that can allow effortless wearing under rough conditions. The twill weave of denim fabrics imparts strength to denim that helps it undergo a great deal of tension, abrasion, and friction before it breaks apart. Comfort comes as a second performance characteristic option for consumers of young age groups. However, denim products are worn by all ages and under a wide range of physical activities and environmental conditions. Therefore, comfort must be considered as a critical performance characteristic of denim products. Developing denim products that exhibit both durability and comfort requires a great deal of trade-off in the design of these products. This is where reliable relationships between performance characteristics and different attributes of the constituting elements (fibers, yarns, and fabrics) must be an essential aspect of denim product design as discussed in Chapter 12. Some of the basic information related to these attributes is summarized in the following sections.

13.1.1.1 Denim fibers

Most denim fabrics are made from cotton fibers; typically, a bale of cotton weighing 480 pounds will yield over 200 pairs of denim jeans. One of the fashion trends of denim fabric is to make denim from organic and naturally colored cotton (e.g., eco jeans by Levi Strauss). The high price of this type of denim is a result of the short supply of naturally colored and organic cotton in comparison with normal cotton and the increasing demand by consumers to use organic goods. Standards for colored and organic cotton products have not been fully established yet, but if the demand continues in this direction, organizations such as the USDA will have to generate such standards. It should be pointed out, however, that the costs of producing organic and colored cottons and the deficiency in some of their inherent properties have made their market volume largely insignificant compared with normal cotton.

Although cotton is unanimously the common choice for denim fabric, other fibers have been used, mostly in conjunction with cotton, to provide additional performance characteristics to denim. For example, scientists and engineers in the Agricultural Research Service of the USDA have developed a cotton-flax blend to be used for making denim fabrics. The underlying concept of this development is to utilize the attributive advantages of both cotton and flax in a blend that can result in a more comfortable denim fabric, particularly in the context of moisture management.

The cotton-flax combination is a development that deserves some elaboration. Like cotton, flax fiber is a natural cellulosic fiber with bulk density equivalent to that of the cotton fiber. However, it belongs to the long-vegetable fiber category with a fiber length that could range from 4 to 40 inches. With cotton fiber length of only 1 to 1.5 inches, blending of the two fibers represents a challenge that must be overcome prior to making a cotton-flax yarn. The two fibers are also different in diameter with cotton ranging from 10 to 14 micron and flax ranging from 40 to 80 micron. Values of some of the basic properties of these two fibers are listed in Table 13.1.

Table 13.1 Values of some basic properties of cotton and flax fibers [3–5].

Fiber attribute	Cotton	Flax
Specific gravity	1.54	1.54
Moisture regain (%) at 65% RH	8.5	10
Moisture regain (%) at 100% RH	Up to 30%	Up to 25%
Fiber tenacity (g/denier)	3.5–5.5	> 6
Breaking elongation (%)	4%–5%	1%–2%
Elastic recovery (%) at 1 g/den stress	About 50%	75%–80%
Elastic recovery (%) at 2 g/den stress	< 40%	65%–70%
Flexural rigidity (g/denier)	60–70	Above 160
Abrasion resistance	Relatively low	Relatively high
Swelling % (increase in area upon water immersion)	Up to 50%	Up to 25%
Wet breaking tenacity (% increase w.r.t dry tenacity)	30%–50%	25%–30%
Heat resistance temperature (°F)	Up to 300	Up to 500

Some of the advantages of adding flax fibers to cotton are higher strength, higher elastic recovery, and higher heat resistance than 100% cotton. However, flax is significantly stiffer than cotton as evident by its higher flexural rigidity. In addition, the breaking elongation of flax is much lower than that of cotton.

What makes a cotton-flax blend a good combination for denim fabric is essentially the moisture management aspect. Flax fabrics provide a very cool feeling when they are worn next to the skin. The reason for this feeling is the inherent wicking ability of flax fibers. Both cotton and flax are cellulosic hydrophilic fibers; they both absorb water and exhibit moisture regain of 8.5% and 10%, respectively, at 65% relative humidity. However, flax fiber has a greater tendency to transfer water via its surface than cotton fiber. This is due to the surface structure of the flax fiber being cross marked in the longitudinal view with multiple nodes along the length held together with a waxy film. As a result, absorption and desorption of water are more rapid for flax fiber than for cotton fiber.

In view of the earlier discussion, the addition of flax to cotton can provide good thermal comfort via the cooling effect caused by water transfer and water evaporation from the skin to the outside environment, particularly in hot weather. Key design factors in this regard include the type of flax fiber used, the type of cotton fiber used, and the percent of flax being added to cotton or the cotton-flax blend ratio. These factors are critical on the ground that a high percentage of flax fibers not only will result in processing difficulty [3] but also more seriously will adversely influence the tactile comfort performance of denim due to its high stiffness.

Other long-vegetable fibers such as kenaf, jute, ramie, and hemp have also been tried in blend with cotton to make denim products [9]. However, issues such as ease of processing, blending compatibility, dye affinity, surface texture, and comfort

represent design challenges to the progress in this direction of product development. As a result, cost can be a major hindering factor against these developments.

Synthetic fibers are also used with cotton to enhance some of the performance characteristics of denim fabric. For example, polyester fibers are used in lightweight denim bottoms to provide better strength and higher abrasion resistance. Spandex is another fiber used in very small amounts with cotton to provide fit and tactile comfort (stretch and recovery) to denim products. As indicated in Chapter 8, spandex is an elastomeric fiber (commercially known as Lycra) made in a filament form of deniers ranging from 20 to 5400 denier. An elastomer is a natural or synthetic polymer that can be stretched and expanded to twice its original length at room temperature. After the removal of the tensile load, it will immediately return to its original length.

It follows from the earlier discussion that cotton fiber is the dominant fiber type used in denim products. This domination should stir the curiosity of many product developers and design engineers as it does not necessarily reflect all target performance characteristics of denim products. Denim fabric is typically a durable product, yet cotton fiber has moderate durability with medium initial modulus and tenacity and low elongation. The elastic recovery of cotton is also low (only 75% at 2% extension and less than 50% at 4% extension). Cotton fibers also act poorly under abrasive effects (e.g., breaking fiber cell walls and damaging fiber tips). However, the positive image of cotton fibers and its well-established effects on comfort and feel performance provide significant merits. The fiber will reasonably absorb water vapor emitted by the body to keep the skin dry. Under dry conditions, the touch and feel of cotton is superior in most apparel products. This is directly due to its tapered and convolutionary surface structure. In addition, the structural features of cotton allow the manipulation of a variety of yarns that can indeed provide a wide range of comfort characteristics. These points provide ample opportunities for product developers in which a combination of durability and comfort features of denim is optimized based on objective and reliable measures. It will be useful, however, to follow the tasks shown in Fig. 13.1, which illustrates an example of the basic steps of raw material selection following the steps discussed earlier in Chapter 7. The reader should refer to the discussion in Chapter 7 to follow these steps.

13.1.1.2 Denim yarns

Denim fabrics are typically made from staple-fiber yarns that can be spun using rotor spinning (open-end spinning) or conventional ring spinning. As discussed in Chapter 9, these two methods of spinning produce yarns that are fundamentally different in structure. The true twist associated with ring-spun yarn makes it stronger and denser than comparable rotor-spun yarn, which typically exhibits a combination of fully and partially twisted fibers and many outer fibers wrapping around the yarns (see Table 9.3, Chapter 9). Ring-spun yarn can also be made softer as a result of the lower levels of twist that can be used to form the yarn in comparison with rotor-spun yarn. These attributes provide positive effects on both durability and comfort.

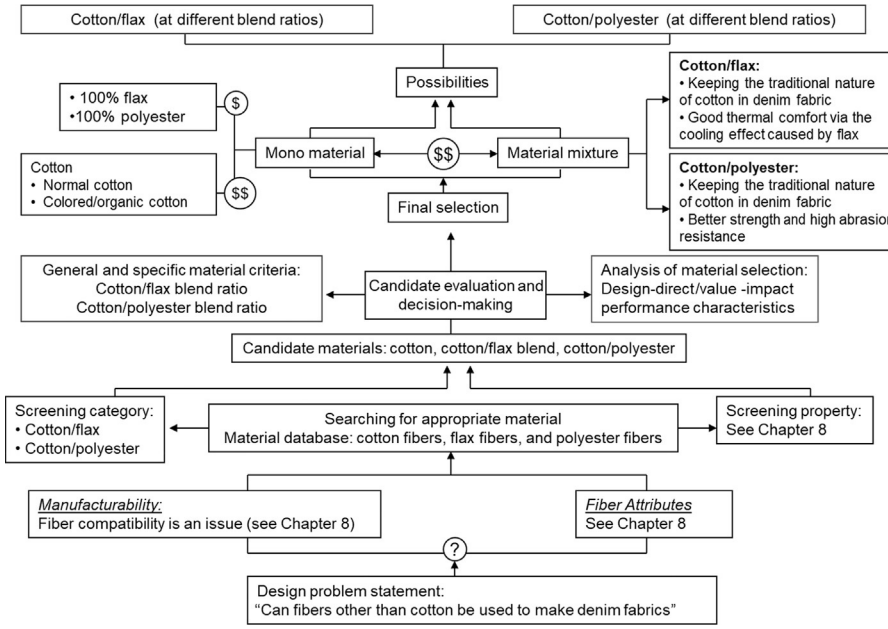


Fig. 13.1 Fiber selection for denim fabric.

Despite the merits of using ring-spun yarns in making denim fabrics, rotor-spun yarns have taken a much larger market share in recent years. This domination largely stemmed from the following reasons [3, 5, 10]:

- Rotor-spun yarn is more economical than ring-spun yarn by virtue of its higher production rate and the condensed process involved in making the yarn (i.e., no roving or winding is required for rotor spinning).
- Heavy denim fabrics are typically made from coarse yarns (e.g., Ne = 7s to 10s) with a large number of fibers per yarn cross section. This range of yarn count can easily be made on rotor spinning by virtue of its principle.
- Rotor spinning has a better tolerance to some of the fiber defects that cannot be easily tolerated by ring spinning (e.g., neps and short fibers). It can also tolerate blends of primary cotton and waste fibers such as noils, card waste, or recycled fibers.

Studies on denim durability revealed that fabrics made from rotor (open-end)-spun yarns were less durable than those made from ring-spun yarns [11]. However, the difference in durability was not apparent until after 16 wash and wear cycles and was not great enough to affect consumer acceptance. When a superior combination of durability and comfort is of primary concern in denim, ring-spun yarns or a combination of warp ring-spun yarns and filling rotor-spun yarns may be considered. When both warp and filling yarns are ring spun, the denim yarn is commonly termed dual ring spun (also ring × ring, ring-ring, or double-ring spun). This is typically a premium and more expensive denim. Dual ring-spun denim is characterized by special texture

and better softness than that of open-end or single ring-spun yarn. As indicated in Chapter 9, ring-spun yarns can be twisted in two directions, *Z*- and *S*-twist. Almost all denim ring-spun yarns are twisted in the *Z*-direction. In recent years, researchers of Cotton Incorporated developed combinations of yarn twist and fabric twill directions. A denim yarn of *S*-twist was found to add subtle textural effects to the denim fabric.

Another more recent development in denim yarns is the use of compact ring-spun yarns. As indicated in Chapter 9, this is a ring-spun yarn in which fibers are aerodynamically compressed to provide a denser yarn and less hairy surface [5]. The increase in cost associated with compact spinning can be justified on the basis of the lower twist required to make the yarn (softer yarn) at comparable or better strength to that of conventional ring-spun yarn, lower size add-on during sizing, and substantially fewer stops or yarn breakage during rope beaming as a result of the reduced hairiness. The yarn is also expected to yield a fabric with greater abrasion resistance.

Denim fabrics are also made from fancy yarns, particularly slub yarns both of ring- and rotor-spun types. The use of slub yarns provides a wide range of appearance to the denim fabric resulting from creating slubs of identical thicknesses but varying lengths, varying thicknesses and lengths, or long sections of yarn with different counts. This direction of development opens many doors for creative fashionable denim fabrics.

13.1.1.3 Denim fabrics

Denim fabric is predominantly made from twill fabric. As indicated in Chapter 10, twill fabrics are used for durable fibrous products that are typically used under harsh physical conditions. For this reason, they are often used in suits, sportswear, raincoats, jackets, and working clothing. The reason for the high durability of twill fabric is that the few interlacing per inch in the twill structure (Fig. 10.1C, Chapter 10) allows higher fabric counts or more yarn packing. This feature also results in low air permeability and high wind resistance. Twill fabrics with steep twill lines are typically stronger than those with reclining or with regular twill lines [12]. They also tend to be unbalanced in construction, as they have a higher proportion of warp yarns than filling yarns per inch. Most denim is made from warp-faced twill fabric. In other words, their warp yarns lie predominantly on the face of the fabric, or warp yarns must always float over more filling yarns than they pass under (e.g., 2/1, 3/1, or 3/2 interlacing patterns). This is also one of the reasons why the blue warp is more dominant than the white filling in blue jeans.

Twill denim is typically divided into three main categories [3, 12, 13]: left-hand twill, right-hand twill, and broken twill. These categories refer to the direction at which the denim is woven. Typically, left-hand twill denim is known to be softer to the touch than right-hand twill. It is also easier to recognize, as the weft threads appear to move left upward as opposed to right upward. Broken twill contains no distinct direction of weave. It has no directional effects. In other words, it does not run to the right or left; instead, it exhibits an alternating right and left with the end effect resembling a random zigzag pattern. The development of broken twill

was originally inspired by the need to combat the twisting effect or fabric torque that was a characteristic of regular twill. Balanced yarn tension and minimum fabric twisting can be obtained from alternating twill directions.

In addition to the unique fabric structure, denim derives its texture and familiar nature from many other sources such as the method of dyeing and the method of drying. The reason denim tends to change color by exhibiting color fading is that the blue warp yarns on the fabric face are dyed with indigo dyes in such a way that only the fibers near the yarn surface are colored, leaving the fibers in the yarn center uncolored. Abrasion effects during use (due to repeated wearing, washing, and drying) typically result in removing the blue fibers partially and exposing more and more white fibers. Indigo is a poor dye by virtue of its low affinity for the cotton fiber. As a result, it does not migrate to the white filling yarns.

13.1.1.4 Denim finishes

A significant aspect of denim product development is surface finish. The impact of this aspect on consumer's acceptance often outweighs most of the other factors contributing to denim performance. Many approaches have been taken to improve denim softness and surface texture. The two prominent approaches are stone wash and enzyme treatment [11, 14–18]. Stone wash aims at providing a fashionable stressed or deformed appearance (e.g., fuzzy texture, puckering at the seams, and slight wrinkling) to denim. The process of stone washing involves drying the denim garments using pumice stones to abrade the fabric surface. This is a colorless or light gray stone or volcanic glass formed by solidification of lava, which is permeated with glass bubbles. In stone washing, factors such as garment/stone ratio, the shape, the size of the stone, and the tumbling time can make a difference in the final appearance of the garment [15]. The drawback of stone treatment is the possibility of creating more distortion than anticipated leading to severely abraded spots on some areas of the garment. This effect can be reduced using some oxidizing agents such as sodium hypochlorite or potassium permanganate but only at reduced tumbling time as the oxidizing agent can also result in physical damage through oxidizing the molecules of the indigo dye.

Cellulase enzyme washing is also used as a safe alternative to stone washing [14]. This is a natural protein that physically degrades the surface of the cotton fibers giving similar appearance to that achieved by stone tumbling. Enzyme treatment also helps in conserving water, time, and energy. Two classes of cellulase enzyme can be used [14, 15]: acid cellulase, which works best in the pH range of 4.5–5.5 and exhibits optimum activity at 50°C, and neutral cellulase, which works best at pH 6 (can be effective at higher pH of up to 8) and provides maximum activity at 55°C. Enzyme treatments yield soft handle and attractive clean appearance of denim at minimum damage to the surface of yarn [16]. They are also inexpensive in comparison with stone washing. Indeed, they can add value to denim fabric via transforming some low-grade denim to a top-quality product due to the removal of fabric hairiness and pills. Other cost benefits associated with enzyme treatments include treatment of larger quantities of garment at once, less labor intensive, and lower damage to seam edges and badges.

Other types of finish that have been implemented more recently include [3, 12] sand blasting, mechanical abrasion, ozone fading, water jet fading, and laser treatment. The principle of sand blasting is to blast an abrasive granular soil through a nozzle at very high speed and high pressure onto specific areas of the garment surface to give a desired distressed and abraded appearance. This is a purely mechanical process in which no chemicals are used. Denim fabric can also be mechanically abraded via robotic techniques to create surface effects such as sueding, raising, or brushing.

Ozone fading is based on bleaching the garment in washing machines with ozone dissolved in water or fading denim using ozone gas in closed chambers. This method serves the fading purpose at minimum or no loss of strength. It is also environmentally friendly since after laundering, ozonized water can easily be deozonized by UV radiation. Water jet fading is based on using hydro jets for patterning or altering the surface finish and the texture of denim garment. In this method, the extent of achieving color washout, clarity of patterns, and softness of the resulting fabric are related to the type of dye in the fabric and the amount and manner of fluid impact energy applied to the fabric.

Laser treatment is a technique used for fading denim fabric by creating patterns such as lines, dots, images, text, or even pictures. Some of the laser systems use a mask to give the desired shape required on the fabric surface. The laser projects through a lens system, which expands the beam. This beam is passed through the shaped mask that comprises an aperture of the desired shape and is then deflected by a mirror to strike the fabric substrate. The duration of exposure determines the final effect on the fabric. Laser treatment can be used to create localized abrasive effects or fabric holes.

13.1.2 Denim product design

The design of denim products can be achieved using the key design aspects discussed in Chapters 4 and 5. As illustrated in Fig. 13.2, a design cycle is initiated after design planning in which the design problem is identified and defined and upon establishing design conceptualization.

The design analysis associated with denim products can be overwhelming, particularly if a new product idea is proposed. In most situations, this analysis will focus on the following key aspects [3]:

- Determining the appropriate fiber or fiber mix that is suitable for the desired denim product.
- Performing basic structural analysis of fibers, yarns, and fabrics.
- Establishing relationships between the desired performance characteristics and the various attributes of fibers, yarns, and fabrics (performance-attribute diagram).
- Chemical analysis of possible finish treatments applied on the fabric.

Design analysis of denim products should consider both functional and style characteristics. As indicated in Chapter 4, the former implies meeting the intended functional purpose of the product at an optimum performance level, and the latter implies satisfying a combination of appealing factors that are desired by the consumers. Figs. 13.3 and 13.4 illustrate examples of functional characteristics and styling characteristics of

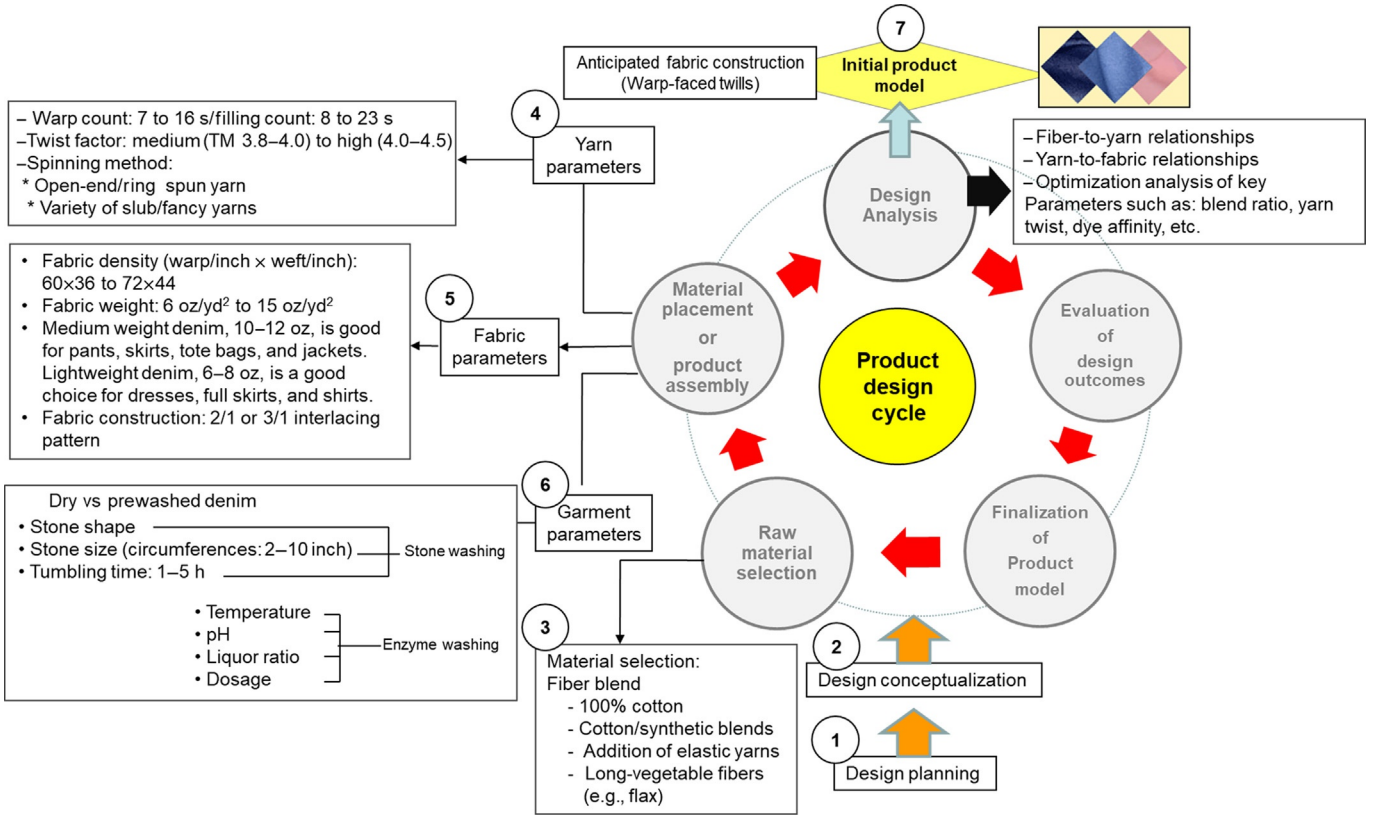


Fig. 13.2 Key tasks of a denim product design cycle.

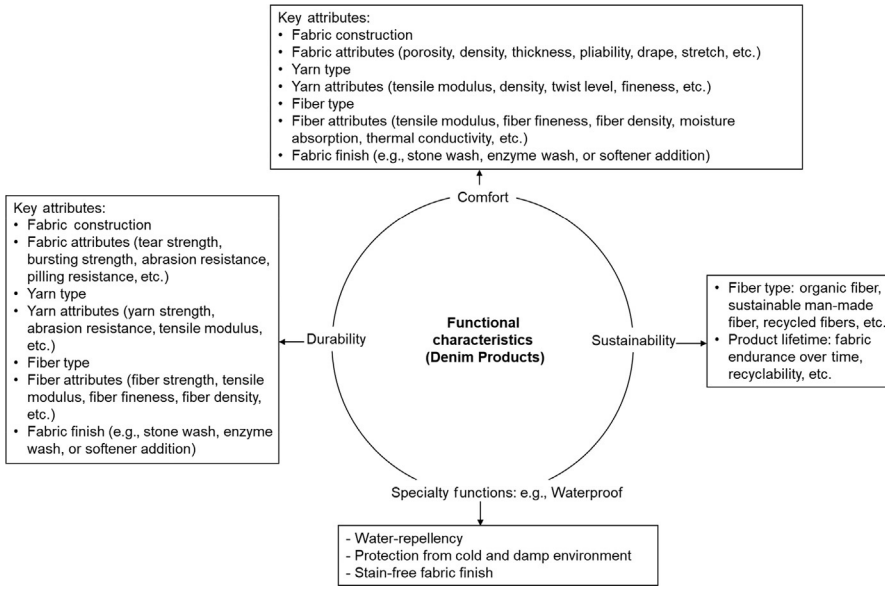


Fig. 13.3 Examples of denim functional characteristics and related attributes.

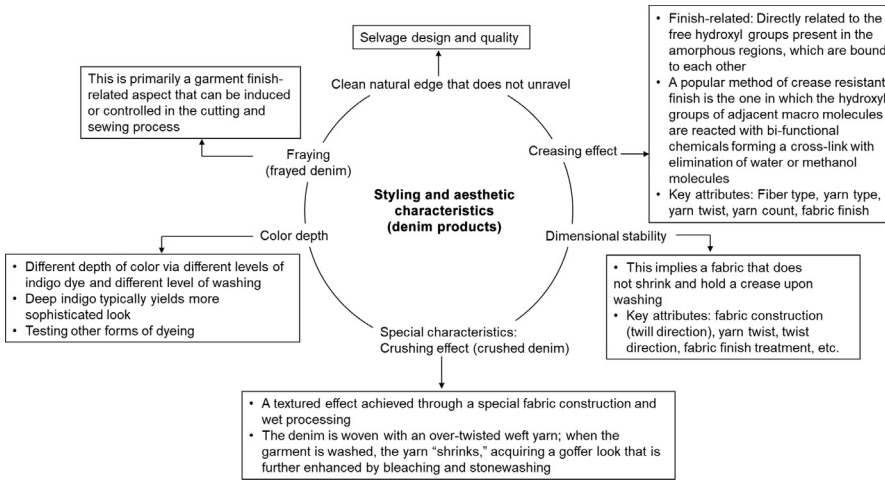


Fig. 13.4 Examples of denim styling and esthetic characteristics and related attributes.

denim products, respectively. Also included in these figures are examples of different attributes that are related to the performance characteristics.

The goal of a design cycle is to reach a viable product model that can be manufactured into actual product. As indicated in Chapter 4, a product model is reached through appropriate analysis supported by technical knowledge and computational

and/or experimental tools. The product model may take different forms including computer geometrical model, mathematical model, or an animated simulation model of product assembly. As the design process approaches the final stage, a full-size prototype model may be constructed and thoroughly tested. In the case of denim products, a prototype model is typically represented by a sample of fabric woven and finished or a complete garment sample that meets the desired design specifications and provides an optimum solution to the design problem. The accessibility of such model will obviously depend on whether the design modification can be made on a finished fabric or garment or it requires substantial changes in all phases of production from fibers to garments.

13.1.3 Denim recycling

With millions of blue jeans being thrown away every year, mostly going into landfills, it is important to incorporate recycling or reusing of denim materials into the overall development process. In general, one can list many approaches to reuse denim fabric. However, consumer's awareness, economical constraints, and technological feasibility are some of issues that need to be considered prior to taking any approach upstream. Large companies such as Levi's developed ways to facilitate denim recycling. It is expanding its recycling program (pdf) to all its US locations, including its outlet stores. Customers will be able to drop off clean, dry clothing or footwear from any brand at their nearby Levi's, and Levi's will work with its partner manufacturers and retailers to recycle denim for famous brands including H&M and Puma. This program is part of Levi's broader sustainability efforts, which also include its program to reduce water use in denim manufacturing.

The common approach to recycle denim products is through fabric shredding into fibers. The recycled fibers can be used in many applications including [3]

- Reprocessing waste fibers through waste-handling spinning operations to make lower grade yarns and fabrics
- Blending waste fibers with other primary fibers to produce yarns and fabrics
- Reprocessing waste fibers into nonwoven products such as utility fabrics, cleaning items, wadding for furniture, cushions and pillows, and car wadding
- Reusing waste fibers in other products such as paper and cardboard

Technologically, the success of any of the earlier approaches will primarily depend on the quality of fibers obtained from the recycling process. For fibers that will be respun into yarns, the primary fiber characteristic is fiber length. Typically, fibers of 0.5 inch or shorter are considered short fibers, and they cannot be respun into yarns. These fibers may be used for nonwoven or paper-making applications. The second important fiber characteristic is what may be termed as "prestress history." During the initial processing, fibers are subjected to many mechanical stresses: they are tensioned, compressed, bent, and twisted. Some of these stresses may exceed the elastic limit of the fiber, leading to permanent deformation. In the weaving and knitting processes, additional mechanical stresses are applied on the fibers. During finishing, fibers are further stressed while being treated thermally, mechanically, or chemically.

These various forms of stress certainly influence the performance of fibers during recycling by making them stiff and easily breakable. This problem is commonly handled by blending small proportion of waste fibers with primary fibers so that the latter can act as a carrier and supportive component to waste fibers during recycling.

In case of denim recycling, the primary challenge facing reprocessing waste fibers is color. This is due to the fact that while denim filling is white, denim warp is indigo dyed. Separation of these two yarns in the shredding process is impossible and cost prohibited. In addition, bleaching the fibers to eliminate the indigo dye can face a great deal of difficulty, as it is well known that indigo dye is difficult to remove or mask by bleaching. These obstacles simply mean that color in the recycled product will have to be accepted. On the other hand, the color shade can be controlled through blending with primary white fibers at different blend ratios.

As indicated earlier, cost and economic feasibility represents the primary challenge facing any reclaiming effort. Cost issues are common in almost all recycling efforts. These include (a) cost differences between the waste landfill option and the reprocessing option, (b) the difference between the cost of primary fibers and waste fibers, (c) the availability of continuous supply of the waste material to keep the recycling operation running, and (d) the impact of quality of the recycled end product on its market value. These issues must be resolved in the design analysis of recycled products.

The reuse of denim through using pieces of denim fabrics obtained from waste garments in other household products has represented a campaign by many environmental advocates in recent years. This is a simple approach that requires minimum effort and minimum cost but a great deal of awareness by different consumers of the importance of recycling or reusing waste materials. Using this approach, many creative ideas can be implemented. A quick glance at the Internet can provide the reader with numerous ideas of reusing pieces of waste denim garment.

13.2 Sportswear products

Sportswear products represent a critical category of textiles that is widely used by numerous wearers from soccer kids to professional players in different sports including cycling, running, walking, sailing, boxing, wrestling, swimming, car racing, climbing, basketball, football, and golf. Since the latter part of the 20th century, product development in sportswear has accelerated dramatically due to the realization of the effects of well-designed sportswear on enhancing the physical performance of players and the comfort requirements under different physical activity levels and different environmental conditions. Indeed, no other category of textile products has received more attention in terms of functional and esthetic design than sportswear products. This is due to the increasing market demand for a wide variety of sportswear products and more creative functional characteristics.

Sportswear makers pay a great deal of attention to many aspects of product design including fiber selection, manufacturability, and attribute-performance relationships [19]. As a result, a great deal of scientific research has been devoted to sportswear in

different areas including polymer and fiber science, yarn and fabric characteristics, manufacturing methods, fabric finish, and lamination techniques. In addition, no other textile business has been more connected with its consumers than the sportswear business through huge promotional efforts in which players are the users and the promoters of products. The expectation of better performance characteristics of sportswear has never ceased, and competition between producers has fueled the market for more innovations and more creative ideas. It is truly a unique market in which consumers are willing to pay premium prices for high-performance products.

The development of higher-function sportswear products has been promoted by a continuous strive by players of different sports to accelerate their performance to higher levels. As more physical activity is needed to win games and sport contests, players are likely to face challenges including excessive sweating and fabric stickiness with the player's body, dust collection, heat stress during running, excessive cooling effect, restricted movement freedom, additional weight due to fabric moisture absorption, friction between fabric and player's body, lack of good protection in case of collision with other players or falling on the ground, and high water and air drag. A sportswear product may also be an integral part of a smart system in which body functions are closely monitored during sport activities. As a result, different sportswear products will have different performance characteristics that are directly judged by the users of these products. In addition, some sportswear products may fulfill one performance function but fail to meet other performance criteria. These aspects represent ongoing challenges to sportswear makers that make product development and finding new design solutions a continuous process since performance characteristics of these products must keep up with the rising performance of players.

Product development and design projects associated with sportswear products can be very inspiring and exciting to many design engineers by virtue of the many options available. These tasks require training and skills in many areas including graphics, textile and fashion science, ergonomics, and fabric coating technology. In addition, design engineers must have good knowledge of many material options including microfibers, texturized yarns, breathable barrier fabrics, innovative stretch materials, intelligent textiles, and interactive materials such as phase change materials and shape memory polymers.

13.2.1 Categories of sportswear products

Sportswear products are generally categorized into two main categories [19]:

(a) Professional sportswear in which maximum physical performance is required, player's age range and gender are predefined, the sportswear is likely to be worn for a short period of time, wearing frequency is predetermined, and the climatic condition is approximately constant within the boundaries of the required sport field (indoor or outdoor).

(b) Leisure sportswear in which low to moderate physical activities are anticipated, players age and gender may vary widely, wearing time and use frequency may vary widely, and the climatic condition may also vary.

In the context of product development, the earlier classification will typically lead to broad definitions of the design problem associated with these categories. As indicated in Chapter 4, a broad definition of a design problem may be initiated by establishing a general description of the proposed product and the primary performance characteristics associated with each category of products. For example, a broad definition may lead to describing two types of performance, namely, activewear performance, and sportswear performance. An activewear may refer to garments that are intended to provide a combination of esthetic, style, comfort, and functionality in a less competitive mode such as casual wear and exercise. Examples of activewear products include parkas, hoodies, pants, and crew neck fleece sweaters. Activewear may also include accessories and footwear of many varieties. A sportswear performance on the other hand refers to higher activity levels, perhaps in a competitive mode and under extreme climates. This necessitates different levels of functional characteristics associated with different sports.

Sportswear products may also be categorized strictly based on the weather condition under which the sport is performed. In this case, products may be classified as (i) cold weather products, (ii) moderate weather products, and (iii) hot weather products. They may also be categorized based on the specific type of sport in which the product will be used. In this case, sportswear product may be divided into many types including autoracing wear, football wear, basketball wear, cycling wear, martial art wear, skiing wear, soccer wear, and Yoga wear. These classifications require more specific definitions of the design problem as discussed in Chapter 4.

13.2.2 Performance characteristics of sportswear products

In the marketplace, most sportswear products are characterized by general performance features such as fit, stretch, color, and maintenance (washing and drying). In the context of product design, key performance characteristics of sportswear

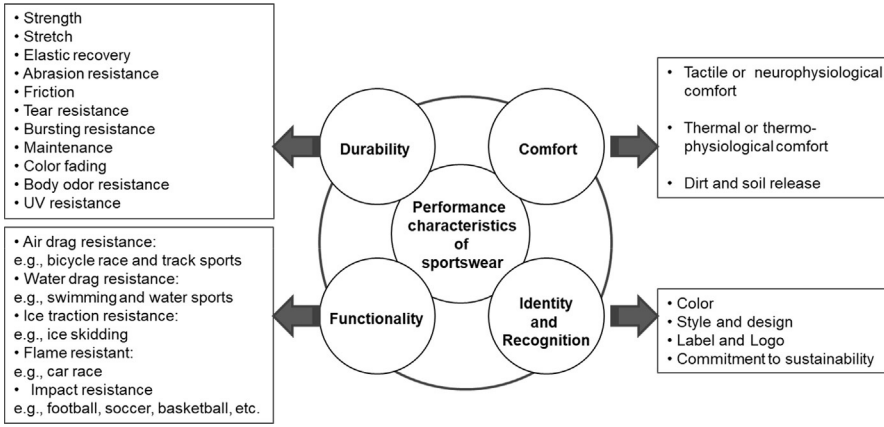


Fig. 13.5 Primary categories of performance characteristics of sportswear products.

products can be divided into four major categories as shown in Fig. 13.5: durability, comfort, functionality, and identity or recognition [19, 20].

Durability characteristics include strength, stretch, elastic recovery, abrasion resistance, tear resistance, color fading, body odor resistance, and UV resistance. The levels of these characteristics will vary with the level of physical activity and the climatic condition in the intended sport. In a survey conducted by the author's company (https://www.el-publish-learn.com/) in 2015, one of the main reasons for rejecting some sportswear products was material failure to withstand high levels of physical activities and extreme climate conditions as evident by loss of elasticity after repeated use, color fading, and tear concentration at the knees and elbows due to high friction and obvious thinning in some areas of the garment. From a design perspective, sportswear products should be well constructed, and reinforcement may be required at the seams and in vulnerable parts of the product in which high rubbing effects are expected.

Comfort is the most dominant performance characteristic of sportswear. Many sports are rigorous and harsh enough even with a virtually naked body. Sportswear products are commonly used for uniformity, identity, protection of the human body, and stability. They should not represent an added burden to the wearer by creating an added load to the human body, restricted movement, or uncomfortable environment due to failure of accommodating environmental and body conditions. Therefore, the key design problem in many sportswear products is to achieve a combination of tactile and thermal comfort. Ergonomic aspects must also be considered in the design analysis. As discussed in Chapter 5, neurophysiological or tactile comfort of clothing refers to the feel of fabric against the skin and the accommodation of clothing to body movement. Thermophysiological or thermal comfort of clothing refers to the fact that clothing represents an intermediate media between the human body and the surrounding environment; as a result, it should act as an adjusting or a controlling system for the sake of accommodating the effects imposed by many thermal factors such as air temperature, radiant temperature, humidity, and air movement. The design problem for comfort should not be resolved by merely producing products of loose or tight fit as this represents only one aspect of design. In this regard, the reader should refer to the discussion on design-problem models for comfort in Chapter 5.

In addition to durability and comfort, some sport applications require special performance characteristics. For example, bicycle race and track sports require minimum air drag resistance, swimming requires minimum water drag resistance, ice skidding requires optimum ice traction, and car racing requires high flame resistance. In design projects, these performance characteristics should be handled through establishing specific definitions of the design problem and developing reliable performance-attribute relationships.

Finally, identity or recognition has become an essential criterion of sportswear products. In today's sportswear market, fashion and trends have become the primary promotional tools, even more than technical trends. As a result, many sportswear items are typically discarded after a short period of use despite being in great conditions. As indicated in the survey mentioned earlier, many consumers particularly those of young ages tend to discard sportswear products for falling out of style. From a

sustainability perspective, this adds to the serious issue of consumer's overstock and the disposal of products that end up in landfills as discussed in Chapter 6. Given the fact that a significant proportion of sportswear products is made from nonbiodegradable fibers adds significantly to this problem. This issue places a great deal of responsibility on sportswear makers to design long-lasting products and assure sustainability in their practices. Options such as the use of recyclable and biodegradable materials, design products of multifunctionality, emphasize durability, and monitoring the flow of sportswear products from fiber to postconsumer are all key aspects in sustainable design. It is critical that sportswear makers beware of the fact that extending the average life of sportswear clothes, which is currently below 2 years, by only 20% of active use per item could mean substantial reduction in carbon, water, and waste footprints.

13.2.3 Fiber types used for sportswear

Fibers used in sportswear range from conventional fibers (natural and synthetic fibers) to specialty fibers designed to meet specific performances. Conventional fibers used include cotton, long-vegetable fibers, nylon, polyester, viscose, polypropylene, and acrylic fibers. Important attributes of these fibers were discussed in Chapter 8. Another fiber that is commonly used in numerous sportswear products is spandex (Lycra). This fiber is used at small percent (10%–20%) with cotton, nylon, or polyester fiber to provide stretch and better fit. Recall that spandex is segmented polyurethane in which alternating rigid and flexible segments that display different stretch resistance characteristics form the fiber. The rigid segments are normally prepared from MDI and a low-molecular-weight dialcohol such as ethylene glycol or 1,4-butanediol, while the flexible segments are made with MDI and a polyether or polyester glycol. The rigid segments have tendency to aggregate, and the flexible segments act as springs connecting the rigid segments that can stretch to great lengths, yet they have greater stretch resistance than other rubbers and do not fail easily under repeated stretching. They also have moderate strength, high uniformity, and high abrasion resistance.

The use of cotton in sportswear products has declined over the years due to the use of many alternative synthetic fibers. It is well established that cotton fiber has excellent comfort properties in the dry state. However, it faces many challenges at higher ambient temperatures or high physical activities as a result of being saturated with perspiration. The capillary capacity of cotton is extremely low as a result of the longitudinal geometry, which is a twisted-ribbon shape along the length of the fiber and a kidney-shaped cross section [20]. The lumen collapse of cotton yields a convoluted surface of the cotton fiber. In addition, it has many folds and reversals of fibrillar texture prominent on the fiber surface. One approach to solve this design obstacle is to blend cotton with other synthetic fibers that have better wicking capacity. Water repellent treatment applied on cotton yarns or fabrics is another option.

Polyester fiber is another common fiber used in numerous sportswear products. As discussed in Chapter 8, polyester is a hydrophobic fiber as it exhibits low moisture absorption capacity. However, the use of polyester fiber in moisture and sweat

management of sportswear is based on its wicking rate, which is much faster than cotton fiber. As a result, it can be designed in to provide thermal comfort through controlled moisture transfer between the body and the external environment. Microdenier polyester fibers can provide a great deal of moisture management by virtue of their high capillary effect for the transportation of liquid perspiration and rapid evaporation. Polyester fiber can also be manufactured in different cross-sectional shapes to enhance moisture management characteristics. In addition, hydrophilic coating can be applied to polyester fibers to achieve an absorption/wicking performance combination. It is also well known that any finish used to increase hydrophilicity will likely to also increase the ability of fabric to release dirt and soil. As discussed in Chapter 8, polyester fibers can be made of high tenacity, which enhances the durability of sportswear.

Nylon 6 and 6,6 fibers are also used in sportswear products because of their higher moisture absorption characteristics in comparison with polyester fibers. They are exceptionally strong leading to more durable sportswear products, and they exhibit high flexibility (low tensile modulus and low flexural rigidity), which makes them useful in providing tactile comfort in sportswear products. They are commonly used in swimwear and cycling wear or as reinforcement fiber in sport socks. Nylon fibers used in dense woven fabrics allow minimum air permeability, which enhances windbreaking performance in many sports garments.

In addition to conventional fibers, many specialty fibers have been developed for the sake of providing special functions to sportswear products. As indicated in Chapter 12, many performance characteristics of textiles require special surface attributes. One of the key design parameters in this regard is fiber cross-sectional shape. This parameter can be manipulated in synthetic fibers to provide special performance features [21]. Table 13.2 shows examples of common cross-sectional shapes that are commercially available and their key design merits. In recent years, design engineers of synthetic fibers have taken a leap in realizing and utilizing fiber cross-sectional shape as a powerful functional parameter [22–25]. As a result, fibers with more

Table 13.2 Examples of common fiber cross-sectional shapes [21].

Cross-sectional shape	Special features
(a) Circular 	– Used in most synthetic fibers, reference for other cross-sectional shapes (a circular shape factor is one) – It has a low surface-to-volume ratio
(b) Hollow 	– Lower density at the same diameter, higher bending resistance, entraps air to provide thermal insulation, light scatter by internal surfaces leading to soil hiding and translucency characteristics
(c) Trilobal 	– Often used to provide higher bending stiffness and soil hiding characteristics
(d) Ribbon 	– Larger flat surface for sparkling appearance, directional bending characteristics

sophisticated cross-sectional shapes were developed. Examples of these developments are listed in the succeeding text:

- *Nylon and polyester hollow filaments*. These have been used for multifunctional sportswear products because of their light weight and quick drying. They can be made 20%–25% lighter than conventional solid filaments. However, these fibers should be treated carefully during processing as they can be damaged by mechanical processes and during texturing or weaving. In addition to light weight, hollow fibers can provide a great deal of flexibility, better wicking, and better thermal insulation than solid fibers of the same polymeric base.
- *C-slit cross-sectional shape* (Fig. 13.6A). This was developed to entrap air for thermal insulation while simultaneously improving elastic behavior [22]. The C-shaped sheath originally has an alkali-soluble polymer core reaching the external surface through a narrow longitudinal slit. After drawing, the filaments can be textured by false twisting or other means. The core is then removed using alkali finishing, giving a hollow C-shaped cross section with a longitudinal slit. The combination of texturing and cross-sectional shape provides void fraction exceeding 30% and a springy feeling. Different fibers including polyester or polyamide based can be used. In another derivative, the sheath can be made of a blend of polyester and hydrophilic polymer [23]. In this case, alkali finishing introduces microcrazes and pores throughout the sheath, which allows liquid sweat absorption and transportation from the skin to the hollow core. This feature allows dryness rather than thermal insulation, which is critical in many sportswear applications.
- *The 4DG fibers* (Fig. 13.6B). This was developed by Eastman Chemical to provide several deep grooves that run along the length of the fiber [24, 25]. The expanded surface area of this fiber provides about three times the amount of specific surface per denier compared with

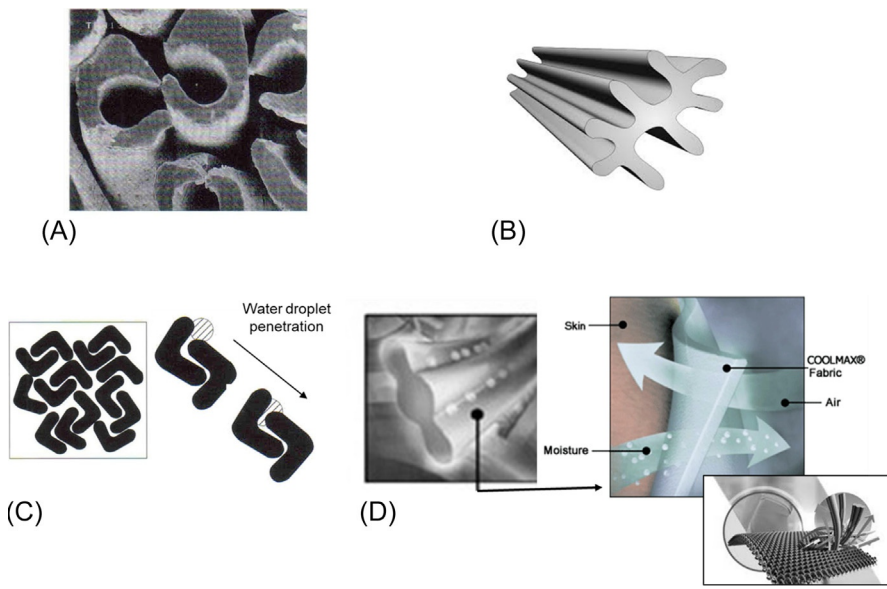


Fig. 13.6 Specialty cross-sectional shapes [21–25]. (A) C-Slit. "Killat N"-Kanebo Ltd.; (B) 4DG Eastman Chemical; (C) L-Shaped Nylon Cross-Section "Ciebet"-Asahi Chemical Industry Co., Ltd.; (D) Four-channel fiber (COOLMAX).

circular fibers. The geometry of cross section can allow transporting of up to 2 L of water per hour per gram of fiber (high capillary wicking). The grooves in a 4DG fiber are also good for trapping particles in an air or liquid stream. These grooves provide areas where eddy currents will preferentially deposit particles and where particles can collect without blocking pores in the fabric. These fibers provide increased filtration efficiency without increase in pressure drop across the fabric. The air entrapping also provides increased thermal insulation, which is suitable for sportswear products.

- *The L-shaped fiber produced by Ciebet* (Fig. 13.6C). This was developed to enhance the wicking performance of sportswear. It produces close packing in conjunction with surface water wettability or wicking effect, derived from the capillary forces created in the interfiber volume that are claimed to be sufficient to wick away liquid sweat. These fibers are also claimed to eliminate the need for wettability surface treatment [26].
- *COOLMAX fibers developed by DuPont* (Fig. 13.6D). This is a proprietary polyester or nylon fiber with unique engineered multiple microchannel cross sections. The purpose of this fiber is to provide moisture management to sportswear. It is also claimed to provide comfort through significant breathability (or air permeability).
- *GORE-TEX fibers*. This fiber was discussed earlier in Section 11.3.2.1 of Chapter 11.

13.2.4 Yarn types used for sportswear

In most design projects of sportswear products, yarns are treated as carrier of fibers or transmitters of fiber properties to the fabric structure. It is important that design engineers beware of the critical role of yarn as an independent structure. It is true that a yarn is essentially a carrier of fibers. However, the way fibers are consolidated in the yarn structure and the extent of freedom of movement of the fibers within the yarn boundaries can have a great impact on the performance of the end product [4, 5]. As discussed in detail in Chapter 9, the yarn structure can determine how many fibers can be accommodated within a given space of the end product, it can determine whether fibers will contribute fully or partially to yarn strength and elongation, and it can also determine whether fibers will act primarily by absorption or by wicking in moisture transfer. When yarns are laid in the fabric structure, the transmission of fiber properties to fabric performance will largely depend on whether the yarn is a continuous-filament yarn or spun yarn, open-end or ring-spun yarn, fancy or texturized yarn, coarse or fine yarn, and fully twisted or partially twisted yarn. The hand and feel of fabric are directly influenced by yarn surface texture (flatness, twist irregularities, and hairiness). Furthermore, the third dimension of fabric, or fabric thickness, is often created by the yarn structure. As a result, fabric compressibility and resilience, which are key aspects of tactile fabric, are significantly determined by the yarn type used. Compressibility can be defined as the proportional reduction in the thickness of a material under prescribed conditions of increased pressure or compressive loading. Resilience is the degree to which a material recovers from compressive deformation. These two characteristics can be optimized for a given fabric construction using a variety of yarn structures. These are critical design aspects that must be considered in the development of sportswear products.

In the context of sportswear product development, yarns can be designed primarily for a specific performance or a combination of different performance characteristics.

When durability is the primary performance characteristic, continuous-filament yarns may be considered as a viable option of yarn structure. This is because continuous-filament yarns exhibit the highest fiber-to-yarn strength efficiency. When natural fibers or blends of natural and synthetic fibers are used, ring-spun or compact yarns should be considered as the first choice for durable sportswear products. This is because fibers that are consolidated in these yarns using twisting and yarns are produced at the optimum twist, which is the twist level at maximum yarn strength. Arguably, the contribution of spun yarns toward sportswear durability is primarily determined by the level of yarn twist used. Twist levels that allow flexibility of sportswear products are called "soft twist." These levels range from 5 to 15 turns per inch. At this low level, the yarn results in soft fabrics. Most knit fabrics are made from soft-twisted yarns. For more durable sportswear, twist levels may range from 20 to 30 turns per inch. Ring- and compact-spun yarns can be produced at different twist levels and different twist direction (Z and S) to provide many features to sportswear fabrics.

When a combination of durability and comfort is required in sportswear products, other types of spun yarns can be considered. These include open end-spun yarn and air jet-spun yarns. Fibers in these yarns are consolidated using partial or false twist and outer fiber wrapping. Therefore, these types of yarns are not as strong as the equivalent ring-spun yarn. However, they exhibit greater fiber mobility in the yarn structure than ring-spun yarns. This provides room for higher flexibility in the garment structure and higher porosity, which are critical for both tactile and thermal comfort of sportswear products. A combination of ring-spun yarns in the warp direction of woven fabrics and open end-spun yarns in the weft direction can achieve optimum levels of durability and comfort. Core-sheath yarns can also be used to meet optimum durability-comfort combinations. In addition, stretch and elastic recovery of sportswear fabrics can be enhanced using yarns made from fibers of high elastic recovery in staple or filament yarn forms. Textured yarns represent another approach to enhance stretch and elastic recovery. When exceptional elastic recovery is required, spandex (Lycra) can be added as a separate yarn or in a core-sheath structure as discussed in Chapter 9.

13.2.5 Fabric types used for sportswear

A textile fabric represents the final platform of sportswear products as it constitutes all the elements required to meet the expected performance characteristics. Sportswear products can be made from woven or knit fabrics and of various constructions, patterns, and colors. Woven structures are commonly used for durable sportswear products and high physical activities. Different woven constructions have been used for making sportswear products, particularly plain and twill weave. A common example is twill weave made from polyester fibers typically used for American football shorts. This type of fabric exhibits both good softness and moderate-to-high strength. Examples of knit fabrics used for sportswear applications include a variety of swimwear knit spandex nylon/polyester tricot fabric (10%–20% spandex, 80%–90% nylon/polyester, 160–210 g per m^2 weight and about 58–80 inch width) and polyester honeycomb knit used for sport shirts.

In addition to the conventional fabrics, the demand for high-performance sportswear that can take player's performance to higher levels and new records has driven a great deal of development of specialty sportswear products that rise to the category of technical textile products. Examples of these products include the following [26–36]:

- *Lightweight sportswear*—These are fabrics made from fine denier nylon filament yarns (10–15 den) to make sport jackets that weigh as low as 100g/unit with seamless (welding) using hot melting tapes.
- *Phase-changeable clothing*—These are sportswear fabrics that contain special chemicals that can change from liquid to gel states in response to body temperature so that fabric insulation properties can be controlled in such a way that maintain a constant body temperature even when air temperature changes.
- *Wick-away fabrics*—These are sportswear fabrics that aim at improving the wicking properties of sportswear by drawing moisture away from the skin to prevent a sweaty and clammy feeling. A common example of this type of fabrics is football shirts using the so-called sport wool yarn, which is basically a mixture of real wool and polyester, the wool being highly absorbent fiber and the polyester being essentially a wicking component.
- *Antiodor/antibacterial sport socks*—These are socks that are treated with antiodor and antibacterial treatments to guard against athlete foot fungus.
- *Antifriction sport socks*—In these socks, the outer layer grips the shoe and the inner layer grips the foot so that the friction is taken up by the two layers and not by the foot skin.
- *Self-cleaning sportswear*—These are products that use nanoparticles attached to the fibers that mimic the "lotus" concept discussed in Chapter 11.
- *High-performance swimwear*—These are fabrics that are primarily designed to reduce water drag. This can be achieved using special chemical finish or by mimicking the way sharkskin, or shark scales help sharks glide through the water.
- *Layered skiing sportswear*—These are fabrics used for activities such as skiing and mountain climbing. They consist of a layer of moisture transferring material next to the skin, an insulating layer, and wind- and water-resistant shell garments.
- *Waterproof/breathable sportswear*—These are fabrics coated with polyurethane membrane via direct printing on membrane to create smooth surface and to protect the membrane. Simultaneously, it eliminates sticky feelings of the polyurethane-coated membrane and provides a dry smooth touch to the skin.
- *Water repellent-bonded sportswear*—These are fabrics in which a front superwater repellent nylon stretch woven fabrics are bonded to a back quick-drying polyester knitted fabric leading to a performance combination of light weight, softness, stretch, mild waterproofing, superwater repellency windproofing, perspiration absorbing, and quick drying.

The examples listed earlier clearly reveal the significant transition toward function-focus sport products. The list also indicates that most of the new developments are geared toward comfort. As indicated earlier, the key performance characteristics of sportswear are durability, comfort, functionality, and identity. Design for durability has been well achieved as a result of the availability of many fibers that can provide a great deal of durability-related attributes. The concept of making durable products through appropriate yarn structure and durable fabric construction has also been well established over the many years of experience of the fiber and textile industry. In addition, the industry has a long experience with fashion, color, and style. Comfort, on the other hand, has been treated for many years as a by-product of the inherent

characteristics of fibrous structures (flexibility, drape, elastic recovery, fit, etc.). The list of developments mentioned earlier indicates that thermophysiological comfort represents the center of the design activities of the new products. It will be important therefore to dwell on the concept of thermophysiological comfort as this area of development still has endless potentials for further innovations in the years to come.

13.2.6 Examples of commercial sportswear fabrics

According to a report titled "Global Sportswear Industry Research Report, Growth Trends and Competitive Analysis 2018–2025," by QY Research (https://www.globenewswire.com), the sportswear market was valued at US$ 84.1 billion in the year 2018 and is expected to touch a valuation of US$ 108.7 billion by the end of 2025. This is by far is the most growing textile and apparel market in the world. The combination of sportswear and fashion represents the major trend in the sportswear market. The global market for sportswear is tremendously booming because of the rising participation in fitness and sport activities throughout the predicted period. In this section, only few examples of advanced sportswear products are mentioned for the sake of illustrating the current directions of product development in this large field.

Sportswear products in the marketplace are often described by market-related categories. In this regard, numerous categories are available commercially. Examples of these categories include (a) basic activewear, which is used for any sport, exercise, or activity that might require comfort and stretch wear; (b) athleisure wear, which represents casual clothing that is considered acceptable and stylish for both fitness activities and daily everyday wear equally; (c) athlete tested, which represents garments that have been tested during exercise by skilled sport people in an effort to meet the needs of the intended sport or activity; (d) compression sportswear, which represents flexible lightweight garments; (e) high-performance sportswear, which represents more technical garments with specific functions suitable for different climates and different levels of physical activities; and (f) reinforced sportswear, which represents some form of garment enforcement in areas that may need extra bracing during physical activity.

On the technical side, the most value-added commercial sportswear products are those designed for thermophysiological comfort. The design of these products is based on meeting three key performance characteristics: thermal regulation, moisture management, and wind resistance. Most sportswear garments developed for thermal regulations aim at keeping body heat at the thermoneutral zone (within an optimum temperature of 37°C ±1°C). Some sportswear garments used in cold weather are designed with good realization of radiant heat loss (through the use of infrared reflective materials and insulative materials) and convective heat loss (through a wind barrier). A commercial example of this category of garments is the so-called X-Static, developed by InSport International, which has a pure silver surface coating aiming at reflecting all radiative thermal energy, produced by the body in cold weather. In hot environment, the makers of "X-Static" claim that silver, being an excellent conductive element, can quickly distribute the conductive energy produced in hot weather to the environment, keeping the wearer cooler.

As indicated earlier, moisture regulation sportswear fabrics primarily aim at removing perspiration quickly so that the fabric remains dry without undergoing dimensional instability (shrinkage and shape loss). The concept underlying the development of most moisture-management sportswear fabric is illustrated in Fig. 13.7. As shown in Fig. 13.7A, the presence of moisture absorbent fabric against the skin can create discomfort as it will store the sweat of a wet body via absorption and create high moisture capacity between the skin and the fabric. Replacing the absorbent fabric by a wickable fabric (Fig. 13.7B) can result in rapid flow of moisture through the fabric leading to cooling evaporative effect and low moisture capacity in the skin/fabric interface. One of the familiar examples of commercial moisture-management fabric is the so-called drirelease, developed by Optimer. This fabric is developed with copolymer polyester acting as the wicking media. The yarn is also treated with antiodor

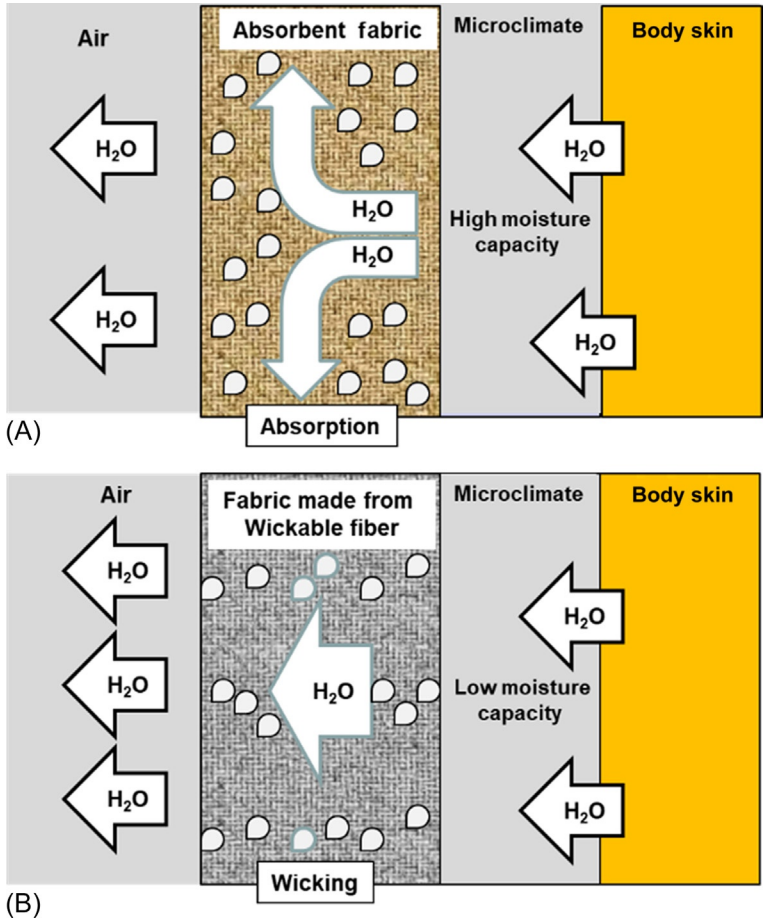


Fig. 13.7 The concept underlying moisture-management sportswear: (A) absorbent fabric against the skin; and (B) wickable fabric against the skin.

finish (Freshguard), which is a permanent protection technology that is claimed to virtually eliminate body odor. Fabrics made from this yarn are used for shirts, tanks, singlets, shorts, and socks. Another example of moisture-management fabric is the so-called Ever Dry, developed by Perfectex, which is a special fabric with wicking function provided by the shape of the filaments of the yarn not added by a chemical wicking material. This fabric is completely washable, and the wicking is permanently retained. The filaments of Ever Dry allow a ditch to exist between the filaments. This ditch provides an excellent conduit for moisture. Perspiration can flow quickly through the fabric during exercise and diffuse quickly and vaporize, allowing the surface of the skin to stay dry, breathable, and comfortable. Ever Dry is available in either nylon or polyester for T-shirts and all exercise wear. The same company also produces fabrics with special coatings or inserted membrane to provide windproof; waterproof or water repellent; anti-UV; antibacterial; and breathable for skiwear, raincoats, jackets, and backpacking products.

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Performance characteristics of technical textiles: Part I: E-textiles

14

14.1 Introduction

From this chapter on, the focus will be shifted to the subject of technical textiles. The term "technical" is introduced to this category of textiles not to imply that traditional textiles were not highly technical and often very sophisticated but rather to reflect the enormous expansion of the use of fibrous structures into many nontraditional applications with specific technical functions. Therefore, before proceeding with the discussion on technical textiles, it will be important to emphasize key points that must be considered in the developmental transition from traditional textiles to technical textiles. These are as follows:

1. Technical textiles are primarily initiated from traditional textiles that have been modified using a multiplicity of chemical or structural treatments to provide nontraditional reactive performance characteristics.
2. The building block of technical textiles is fiber. Therefore, fiber type, fiber chemical and morphological structure, and fiber attributes must represent the primary design criteria of technical textiles.
3. When yarn-based fiber assemblies are used, yarn type, yarn structure, and yarn attributes must be considered in the design of technical textiles.
4. When woven or knit fabrics are used, fabric type, fabric construction, and fabric attributes must be considered in the design of technical textiles.
5. When nonwovens are used, key parameters such as thickness, fiber density, and bonding method must be considered in the design of technical textiles.
6. The role of fiber and fabric finish is extended for technical textiles beyond the approaches used for traditional textiles. Fiber and fabric finish could be the key design aspect in achieving critical performance characteristics including conductivity, stain or water repellence, flame retardance, antistatic behavior, antibacterial behavior, UV protection, and insect repellence.

In view of the earlier points, any design project aiming at developing technical textiles must begin with basic knowledge of fibers, yarns, and fabrics. In this regard, the concepts of product development and design conceptualization discussed in Chapters 3–6 can be applied directly to technical textiles. However, in contrast with the development of most traditional fibrous products, where ideas often stem from conventional wisdom, fashion or style change, and long experience with existing products, the development of technical textiles stems from full realization of the specific function of the fibrous structure in relation to the integrated assembly of the end product. This is a direct result of the fact that technical textile components are hardly

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stand-alone products as they must be used in conjunction or in adherence with other components of the final product assembly. It is important, therefore, to evaluate generated ideas not only in view of the performance characteristics of the fibrous assembly but also in view of the performance of end-product assembly or subassembly. This is a key aspect that should be highly emphasized in the design conceptualization process.

Design engineers of technical textiles should also be highly knowledgeable in the applications in which fibrous assemblies are used. For example, the design of fabric for automobile airbags should be based on good knowledge of the airbag system components and its deployment mechanism. Similarly, the design of a certain type of suture for medical application requires knowledge of the factors influencing and influenced by using such suture. For these reasons, the development of technical textiles involves examination and analysis of performance characteristics that are extended beyond the conventional characteristics discussed in the previous chapters. The key, however, is good understanding of fundamental concepts and basic characteristics of fibers, yarns, and fabrics. This point is very important particularly in view of the transition that many schools around the world have made in recent years, which is from a focus on traditional textiles to a total emphasis on technical textile science. In this transition, there is often a tendency to minimize or eliminate ties with traditional concepts and technologies. It is the author's opinion that a great deal of what we know today about technical textiles has originated from our knowledge of these traditional and fundamental concepts. It is important, therefore, not to break the bridges between traditional and technical textiles.

Unlike the traditional textile products, where one can find common performance characteristics applicable to almost all products, technical textiles will have different types of performance characteristics and different levels of these characteristics depending on the specific application under consideration and the extent of meeting the requirements of this application. Therefore, it will be difficult to establish performance characteristics, attributes or design parameters that are common to all products, and any discussion of these aspects must be made in reference to the specific product and the application under consideration. Depending on the product category and the specific application, performance characteristics of technical textiles may include durability, dimensional stability, heat resistance, biodegradability, soil compatibility, solar radiation, fatigue resistance, chemical resistance, frost resistance, wind breaking, thermal screening, hail resistance, gas release, and chemical penetration. However, even within a certain performance characteristic, different aspects must be established. For example, durability of technical textiles may be extended beyond strength and mechanical resistance to cover many other aspects such as resistances to environmental changes, radiation, bacterial, and temperature effects. In addition, durability over time is critical for many applications. Some products may be stored for months or even years prior to use (e.g., airbags and some medical products), others may be used in changing conditions from hot to cold or vice versa over time (e.g., protection systems and agricultural-related products), and others may be used for a very short period of time in which intense or severe external effects are applied (e.g., flame-resistant and bulletproof vests). It is important therefore to extend the concept of durability in the design analysis of technical textiles to accommodate these various

effects. The key point in this regard is that a technical textile product cannot be characterized by a single performance characteristic; instead, it will be associated with a combination of characteristics that must be interactively optimized to meet the purpose of the product.

On the market side, many companies in the United States, Europe, and Asia that have been in the business of traditional textiles for many years have shifted toward the developments of technical textiles either by adding functionality features to traditional fibrous products or by switching over to complete lines of technical textiles [1–4]. Many new investors in these markets have entered the business of technical textiles based on two primary assumptions: (a) the value added in these products will bring about sound profits, and (b) technical textiles are likely to be less vulnerable to import and price change. While these assumptions may be theoretically valid, their validity will largely depend on a dynamic strive to develop new products, add new features, and create new markets or expand existing ones. These aspects require a great deal of capital investment, creative engineering work, and time to break even endurance. From a product development viewpoint, the success in the market of technical textiles will largely depend on the extent of change in the industry from a commodity-based industry to a value-added industry. This change requires high levels of investment in product innovations. In addition, design conceptualization must become a key element in the industry structure. Furthermore, developers of technical textiles must invest in market research to identify opportunities and explore new ideas that serve consumers of various sectors. Competition will always be a fact of life, and it is likely to get tougher. This means that innovation and creative ideas should become a continuous streak and not a static establishment. Creative design can indeed yield products that are unique and robust against duplication or imitation. In this regard, gaining information about market needs and their dynamic changes is essential for a growing market.

This chapter marks the beginning of the discussion on applications, key performance characteristics, related attributes, and design aspects of common technical textiles. The focus of this chapter will be on E-textiles (or commonly called smart textiles). This type of products has become an independent category of its own to the point that no one uses the term "technical" to describe it anymore. It is our view that the term "technical" is more appropriate as the level of smartness in E-textiles is still an ongoing process as will be discussed in this chapter. However, going by the common trend, we will adhere to these new terms.

14.2 E-textiles (smart textiles)

Since the beginning of the 21st century, the term "electronic textiles or E-textiles" has become a common term in the universal market of technical textiles. An equivalent alternative term is "smart textiles" or "ultrasmart textiles." This term is generally used to describe functions that have traditionally been performed by humans using various nontextile means and are now supported by wearable systems integrated into the garments that people wear. Therefore, the term "smart" should refer to the integrated

functionality of a product, and more importantly, it should be based on full credit to the product developer who is the primary source of intelligence.

Many approaches have been taken to develop and design E-textiles. They can be made by using conductive polymers, incorporating smart materials, encapsulating phase change materials, adopting shape-memory polymers, or using fabric as a platform for seamlessly integrated actual electronic devices, miniature computers, sensors, or communication devices. The connection between energy and E-textiles is very significant. Virtually, all E-textiles will involve some sort of energy transfer, either between an external stimulus and the material or between human body and the material. The ability for E-textiles to respond or modify themselves in response to external effects will depend on key factors such as moisture content, temperature, pressure, and density. These are largely material-related factors that will depend on the attributes of the fiber assembly (fiber type, fiber properties, yarn structure, and fabric construction). The connection between energy and electronic systems is also well established in applications where flexible devices such as solar cells, field-effect transistors, light-emitting diodes, and photovoltaic devices are integrated into textile platforms. These components cannot operate without enough energy. This aspect adds another key performance characteristic to E-textiles, which is energy harvesting and storage capabilities. This application extends beyond wearable E-textiles to cover a wider range of applications.

The basic design concept of E-textiles is to provide optimum performance of three primary interactive modes: (a) an interactive mode between E-textiles and the wearer, (b) an interactive mode between E-textiles and the external environment or other electronic systems, and (c) an interactive action mode to satisfy the specific purpose of E-textiles. The first mode requires accommodation of all human-related performance characteristics that have been considered in the design of traditional textiles (e.g., aesthetic, durability, comfort, decorative, and fashionable characteristics). This accommodation must be achieved in the presence of the existence of nonfibrous materials in the E-textile assembly. It also requires an optimum responsive ability of an E-textile to body movement and internal or external functions. This ability will largely depend on the type of modification made to textiles and the efficiency of the integrated devices. The second mode is largely functional related, and it will depend on the performance of the added materials (e.g., conductivity, phase change, and shape memory). The third mode will be product purpose related, and it will vary from one product to another. In all these interactive modes, durability and reliability must coexist in E-textiles. In this regard, two significant challenges are added to the design process. The first challenge stems from the fact that wearable systems must be continuously maintained through repeated washing and drying, and the integrity of the product must survive this continuous maintenance process. The second challenge stems from the fact that electronics are products that continue to evolve, sometimes at a very rapid pace. This means that an E-textile can become rapidly obsolete as a result of the development of new enhanced electronics. These two challenges must always be considered in developing E-textiles not only from a market-value viewpoint but also, and perhaps more seriously, from a sustainability viewpoint.

14.2.1 Conductivity of E-textiles

The most important performance characteristic of E-textiles is electrical conductivity. This is because E-textiles must receive, store, and transmit data and signals to meet its primary functions. Electrical conductivity is a material property that indicates the amount of electrical current a material can carry or how an electrical current move within a substance [5,6]. It is commonly denoted by the symbol σ and has SI units of siemens per meter (S/m). The name siemens for the unit of conductance was adopted by the 14th General Conference, 1971, on Weights and Measures as an SI derived unit (it was named after Ernst Werner von Siemens). Electrical conductivity is expressed by the equation $\sigma = J/E$, where J is the magnitude of the current density in amperes per square meter (A/m^2) and E is the magnitude of the electric field (or field strength) in volts per meter (V/m). In water, conductivity is often reported as specific conductance, which is a measure compared with that of pure water at 25°C. Fundamentally, the value of electrical conductivity depends on the ability for electrons or other charge carriers to move within the lattice of a material. Highly conductive materials such as copper allow the free movement of electrons within their molecular lattice. On the other hand, materials with a low level of conductivity or conductance have very few free electrons within their structure. Typically, electrons are tightly held within the molecular structure and require a significant level of energy to set them free.

The opposite to electrical conductivity (σ) is electrical resistivity (ρ) in ohm meter (Ωm), determined for a uniform cross section by the general equation: $\rho = RA/L$, where R is the electrical resistance, A is the cross-sectional area, and L is the length of the material. The relationship between conductivity and resistivity is $\sigma = 1/\rho$. It should be noted that while electrical conductivity is a material property, a closely related term, which is electrical conductance, is a property of an object. Conductance is a mass-dependent property, while conductivity is an inherent or intrinsic property and does not depend on mass. Conductance, on the other hand, will depend on mass, size, dimensions, and shape of an object.

As indicated earlier, materials may be classified as either conductors or insulators. For example, metals, such as copper and silver, allow electrons to move freely and carry with them electrical charge. Rubber or wood is considered as insulators since they hold on to their electrons tightly and will not allow an electrical current to flow. The effect of temperature on electrical resistance is also known to be a material property. In general, resistivity increases with increasing temperature in conductors and decreases with increasing temperature in insulators. However, there is no simple mathematical function to describe these relationships as it will vary from one material to another [5,6]. For example, copper being a conductor will typically exhibit a linear relationship over a wide range of temperature in which resistivity (Ωm) will increase with increasing temperature according to the following formula, $\rho = \rho_o(1 + \alpha(T - T_o))$. In other words, copper remains very conductive at low temperature, and only when temperature increases, it loses some of its conductivity in a linear fashion as resistivity increases. For other materials (e.g., tungsten), the relationship may be in the following form $\rho = \rho_o(T/T_o)^{\mu}$. In view of this

fundamental information, electrical resistivity should be described for a given material at a specified level of temperature. For example, at 23°C, conductors such as silver will have a resistivity of $1.59 \times 10^{-8}\,\Omega\text{m}$, copper will have a resistivity of $1.68 \times 10^{-8}\,\Omega\text{m}$, aluminum will have a resistivity of $2.65 \times 10^{-8}\,\Omega\text{m}$, iron will have a resistivity of $9.71 \times 10^{-8}\,\Omega\text{m}$, and steel will have a resistivity of $7.2 \times 10^{-7}\,\Omega\text{m}$. At the same temperature, silicon will have a resistivity of $6.40 \times 10^{2}\,\Omega\text{m}$, the human skin will have a resistivity of about $5.0 \times 10^{5}\,\Omega\text{m}$, glass will have a resistivity more than $10^{10}\,\Omega\text{m}$, rubber will have a resistivity of about $10^{13}\,\Omega\text{m}$, and sulfur will have a resistivity of $10^{15}\,\Omega\text{m}$.

In view of the earlier points, materials can also be divided into two categories [5–8]: semiconductors and superconductors. Semiconductors are poor conductors. They are materials in which the conductivity is much lower than that for metals, but this can change at elevated temperatures. For example, silicon is typically an insulator at room temperature, but it will conduct electricity when it is heated to high temperatures. Thus, one can say that semiconductors represent a category of materials that are normally poor conductor at low temperatures, but their conductivity increases at higher temperatures. This special ability makes semiconductors the perfect materials for electronic devices. Circuits of small semiconductor switches, called transistors, are at the heart of computer ships and enable them to operate and function very efficiently. Semiconductors have enabled computers and electronic devices to become smaller, efficient, and reliable. It should also be noted that heat is not the only way to change the conductivity of a semiconductor as light, electric current, and electric fields can also have similar effects. Semiconductors have revolutionized information technology; indeed, without semiconductors, there would hardly be information technology today.

Superconductivity is the property describing very low resistivity at very low temperature. At such temperatures, superconductors will lose virtually all resistance to electric current; they become perfect conductors. Once an electric current is initiated in such materials, it continues to flow without diminishing and can go on essentially forever. The discovery of superconductivity has revolutionized the development of many electric products. As it is well known, a large fraction of the electrical energy supplied to some devices is lost in overcoming electrical resistance within the device (heat loss). If the same device is made from a superconducting material, no energy would be lost because there would be no resistance to overcome. A superconductive material will also prevent a magnetic field to pass through it at low temperature.

In E-textiles, conductive materials are used in many applications particularly those that involve monitoring of body functions, communication, heating textiles, and electrostatic discharge clothing [9]. Some E-textiles consist of sensors that can monitor heart rate, EKG, body temperature, moisture, pressure, and other critical body signals. Some sensors require an external power sources, and they are commonly known as passive sensors. Other sensors are categorized as active sensors, and they use input energy to measure different activities. These E-textiles are now commercially available. For example, some companies developed electroconductive fabrics that are placed close to the heart to monitor heart rate through measuring the electric impulses

that the brain uses to control the heart muscle. Other products are designed for runners using conductive fabric on a strap around the runner's chest. Conductive fabrics used for heart-rate monitoring can now be found in T-shirts and bras. Many of these products are still under further development with unlimited potential success. Another category of commercially available E-textiles is electroconductive pressure-sensitive fabrics for touch screen interfaces. These products turn a textile platform into a keyboard and other forms of interfaces. E-textiles are also commercially available for the purpose of heating the human body in cold environment.

As discussed in Chapter 8, the obvious choice of conductive material is metallic fibers that are formed by a bundle-drawing process or by shaving-off process of the edge of thin metal sheeting. Gold and silver are the easiest to draw, but modern methods have allowed the manufacture of steel, tantalum, and zirconium fibers. Stainless steel and copper yarns can be made flexible, soft, and durable enough to be woven or knitted. Metal fibers being good conductors have been blended into fabrics to reduce the tendency to develop static electrical charges. They may also be used as electrodes for monitoring electrical physiological activity such as electrocardiogram (ECG) signals [10,11].

Another category of conductive textiles is based on using conductive polymers or, more precisely, intrinsic conductive organic polymers (ICPs). Fortunately, many polymers are inherently conductive. These include polyacetylene, polypyrrole, and polyaniline. The advantage of using conductive polymers in E-textiles is that the sensors retain the natural texture of the material. However, the problem with these devices is a variation in resistance over time and high response time. The fabrication process may involve polymerization, wet spinning, or dip coating processes [10–12]. Examples of polymer-based applications used for electrical conductivity include the following:

(a) Doping techniques in which exposure of polyacetylene (PA) polymer to iodine vapor increases conductivity by up to seven orders of magnitude. This performance is attributed to redox reactions (charge transfer complexes) between the PA and iodine vapor [12].

(b) The use of conjugated polymer polypyrrole (PPy) that exhibits high conductivity and chemical stability under different external conditions [13,14].

(c) The use of polyaniline (PANI), known as aniline black fabricated via a chemical oxidative polymerization process of aniline. PANI electrical conductivity is due to the partial oxidation or reduction process and can be tuned to achieve the required conductivity for a given application [15]. The production of polyaniline fibers of up to 1000 S/cm conductivity for bulk material using wet-spinning process in which a mixture of organic solvents and the emeraldine base form of polyaniline is used to make a spinning solution, which then enters the first coagulation bath where it solidifies and forms fibers. A second coagulation bath is used while filaments are being stretched then doped with an acid suitable for the preparation of conducting fibers [15].

In addition to metallic fibers, metallic substances can also be deposited into textile platforms using many techniques including vacuum deposition [16,17]. Sputtering or evaporation methods can be used to directly form a thin metal layer on the exposed surface of the fibers, but they are not suitable for depositing metal on porous fibers, and the deposited films are weak against repeated deformations like folding

or bending. Alternative methods used to synthesize metal-based conductive textiles include the use of electroplated or electroless plated metals, liquid metals, and metallic nanomaterials such as nanoparticles or nanowires [18,19].

Conductive E-textiles can also be carbon based using different carbon forms including carbon fibers, nanotubes, nanoparticles, and graphene [18–20]. Many carbon nanotubes are claimed to exhibit electric current carrying capacity exceeding superconductors. They also exhibit many of the attributes discussed in Chapter 8 including high mechanical strength and stiffness, light weight, environmental stability, and superior thermal conductivity. One of the potential applications of carbon nanotubes is their use in electrical wiring. Most electrical wires are typically made from copper and aluminum. These materials are of higher weight that limit their use in aerospace applications, have skin effect that hinders their use in telecommunications, and exhibit electromigration that severely damage microscopic wires in electronic applications. However, it should be pointed out that several challenges are also encountered in manufacturing carbon nanotube electrical wires including preparation of macroscopic structures that retain the properties of individual nanotubes, control over the morphology and dimensions of these structures, and development of large-scale cost-effective manufacturing processes and provide the wires with suitable electrical insulation and connections for integration into electrical systems. These challenges certainly call for creative design ideas in a field that has enormous potentials. These ideas should be based on good understanding of the physics behind the transport properties of these new carbon structures.

14.2.2 Shape memory of E-textiles

The phenomenon of "shape memory" is well known to most people in the classic example of water, which turn into ice when it is frozen and a vapor when it is boiled. The difference between these phases depends on how the water molecules are arranged under different temperature levels; in liquid water, the molecules are loosely packed together so that they can move past one another, and in ice, molecules are tightly packed together, and they can't change places. Even in ice form, multiple solid phases can be observed; there is a hexagonal ice phase that is stable between 32°F and −150°F and a cubic ice phase that is only stable between −150°F and −330°F. Like water, a shape-memory material behaves uniquely under heat, and it can remember a specific shape and change to this shape when it is heated. Shape-memory materials will also have multiple solid phases; the low-temperature phase is called "martensite phase," and as the temperature increases, the atomic alignment changes to another phase called "austenite phase." This means that to set the shape of a material, it must be held in the austenite phase at high temperatures to set the memory shape. When the material is cooled, the material will transform to martensite phase, but it does so without changing the shape; meaning, you can deform it in any fashion, but the material will not change phase, but the alignment pattern may change. This process results in a permanent shape change. When the material is heated up again, it will go through the phase change from

martensite to austenite, and it returns back to its original shape (the reader can watch this Y-tube-video to visualize this process, https://www.youtube.com/watch?v=s62PL5vmfNw). Shape-memory materials also exhibit superelasticity or a complete recovery after deformation. This phenomenon can be seen in some eyeglasses that can be stretched without being permanently bent.

In E-textiles, most shape-memory materials are alloys [21] or polymeric substances [22–26] incorporated into fabric to respond to various stimuli including heat, light, humidity, electric field, and magnetic fields with the ability to remember and recover substantial programmed deformation upon activation and exposing to an external stimulus. The alloys used are essentially metals that have two characteristics: shape memory and superelasticity. The most common alloy used is nickel-titanium (NiTi) that is easily transformable from the martensite (low temperature) phase to the austenite (high temperature). Shape-memory polymers also have the ability to sense and respond to external stimuli such as temperature, pH, chemicals, and light in predetermined fashions. They have various elasticity levels by virtue of their internal structures. They are typically cheaper than shape-memory alloys. Typical examples of shape-memory polymers include polynorbornene, transpolyisoprene, styrene-butadiene copolymer, and crystalline polyethylene.

Applications of shape-memory products include the following.

1. Breathable textiles

As discussed in Chapter 5, the problem-design model of thermophysiological comfort is a complex one by virtue of the multiplicity of factors involved and the multiplicity of media (human skin, fabric, and environment). The use of shape-memory polymer materials has opened the door for more design options as they can assist greatly in regulating the transfer of heat and moisture to human's body through textiles. In principle, the volume of free molecules in shape-memory polymers can significantly increase when temperature exceeds the glass-transition temperature [27–30]. This allows a porous internal structure that allows the transfer of vapor and heat through body perspiration. Below the glass-transition temperature, the molecular free volume is decreased, and heat loss or moisture transfer is restricted. The development of shape memory–based breathable textiles is still considered as an ongoing development, but some products have already managed their way to the market.

Other shape-memory polymeric-based products are used primarily for waterproof and windproof applications. These products are based on the principle of thermal vibration, which is generated by micro-Brownian movements of polymeric chains [31]. In these products, shape-memory polymers can be incorporated into the fabric in the form of a laminate that can adapt to surrounding environmental conditions.

2. Self-adapted and self-retained textiles

The classic approach of adaptable shape in textiles is based on using high elastic and stretchable materials such as spandex fibers, discussed in Chapter 8. Normally, the high stretch of this fiber generates pressure on the wearer, and hot climates can complicate this effect. Using shape-memory polymers, new products are developed in which an optimum combination of stress modes (tension, pressure, bending,

shrinkage, etc.) can be produced using shape-memory polymers that can regulate their structures with changes in environmental temperature. These products can enlarge and adapt to the wearer size, while no significant pressure is being exerted on the wearer due to the shape fixity of the shape-memory fibers. Vertical pressure tests suggest that the garments made with shape-memory polymers possess a relatively low vertical tension stress in comparison with elastic fibers. This can be attributed to the deformability and fixability of shape-memory fibers into temporary shapes, which diminishes the adverse pressure sensation to wearers [31,32].

One of the familiar products available commercially is "wrinkle-free" cotton fabric. This product is not designed based on the inherent properties of cotton fibers or their internal structures as these factors typically result in fabrics that can easily wrinkle making ironing an essential aspect of cotton garment maintenance. The cause of wrinkling in cotton fabric is well known; cotton fiber is made of numerous parallel chains of the polysaccharide cellulose, and those chains are held together by weak hydrogen bonds. When a cotton garment is left sitting in the dryer, the bonds break and eventually reform as the cellulose chains shift into new, kinked configurations. The classic approach to deal with cotton wrinkling behavior is by treating fabrics with molecules that cross-link the cellulose chains to permanently lock them into place. In simple words, it is a process of holding cellulosic molecules with urea-formaldehyde and other cross-linkers to provide some form of memory to cotton so that it can recover its original shape. The finish treatment used to produce wrinkle-free cotton is dimethylol dihydroxyethylene urea (DMDHEU). This cross-linker has four hydroxyl groups capable of forming tight, covalent bonds to cellulose. The problem with this treatment was that it modifies cotton in the presence of an acid catalyst, and therefore, it also weakens the fabric. Over time, DMDHEU also breaks down and releases formaldehyde, one of the starting materials used to make it. For this reason, the textile industry has voluntarily lowered the levels of formaldehyde on garments by capping DMDHEU with molecular groups such as alcohols. For these reasons, shape-memory polymeric treatment of cotton may provide a better alternative. Some studies suggest that shape-memory polyurethane emulsion–treated fabric demonstrated adequate wrinkle-free effect after repeated washing, and it can easily last up to hundreds of laundering cycles [31]. The fabric also possesses a greater crease and pattern retention ability due to the presence of shape-memory effect.

3. Water-managed textiles

The relationship between fibrous structure and water (liquid, vapor, moisture, perspiration, etc.) goes back to the era of early discovery of human clothing. The intimacy of garment with the human body has made water management a critical aspect of thermophysiological comfort. In classic design, the key factor that regulates water transfer is fiber type as fibers can be divided into main categories: hydrophilic fibers that can absorb or release water in its internal structure and hydrophobic fibers that do not absorb water but may allow water penetration through a fibrous assembly by the capillary effect (wicking effect). Other structural factors of yarns and fabrics can also

assist in water-transfer management as discussed in Chapter 5 in the context of thermophysiological comfort. In Chapter 11, fabric finish treatments intended for water management were also discussed including the application of nanoparticles to produce the "lotus" effect. The achievement of an optimum combination of these factors can provide a great deal of thermal comfort except for the fact that thermal comfort is not a static performance characteristic and it can easily change with the change in the external climate.

Water or wettability management can be achieved using shape-memory polymeric treatment. The underlying principle of this approach is that if a shape-memory polymeric coating is used on a fiber surface, it can yield different shrinkage effects after heating and cooling making it potentially useful in water repellence or water spreading applications. In some studies [33], smart cleaning cotton fabrics were produced using cross-linked thermoresponsive polymer, poly(2-(2-methoxyethoxy) ethoxyethyl methacrylate-*co*-ethylene glycol methacrylate). It was found that both the wetting time and contact angle of the cotton fabrics significantly increased, when the temperature was above the lower critical solution temperature (LCST), indicating the cotton surface switches from hydrophilicity to hydrophobicity. Since cleaning performance is normally improved in hydrophilic surfaces, this development can lead to self-cleaning effects or cleaning at lower temperatures.

14.2.3 Product developments and design conceptualizations of E-textiles

The brief review presented earlier clearly indicates that E-textiles require product development strategies and design methods that are uncommon in the traditional textile industry. It is truly an emerging interdisciplinary field in which a wide range of expertise from different fields must join to develop and design such products. In all situations, textile scientists and engineers must represent an integral part of this process. Given the very diverse expertise needed, different members of the product development team must communicate effectively and efficiently with each other. This means that a textile engineer must understand a great deal about information technology, microsystems, different materials (e.g., alloys and polymers), unusual physical and thermal phenomena (e.g., semiconductivity, superconductivity, and thermal vibration), shape-memory aspects (e.g., the martensite and austenite phases), energy manipulation, storage, etc. On the other hand, experts in other field must also understand fundamental textiles, inherent characteristics of fibers, and fibrous structures. In addition, all involved experts in the design of E-textiles must pass the technology challenge as many E-textiles require special fabrications processes. Recall that in the "concept-modeling-optimization-manufacturability" system (CMOM) discussed in Chapter 5, manufacturability represents one of the most critical aspects of design. In E-textiles, this aspect often comes on top as the most critical one since new and nontraditional technologies are often required to integrate electronics into textiles.

The growth potentials in the E-textile market are unlimited. It is an exciting field that has led to a huge interest by numerous textile scientists to the point that many of them have completely switched from traditional to E-textiles, learn new things, and join other disciplines in cooperative research. Furthermore, many textile institutes around the world completely removed traditional textile manufacturing and testing equipment and began to invest in E-textiles. Other factors have also contributed to this change including the economic situation of the traditional textile industry and the migration of many textile companies to cheap-labor regions around the world. However, it is the author's opinion that slower switch could have been wiser, and a dual approach could have been even better. The reasons for this opinion are as follows:

- The home base of E-textiles is traditional textiles as fibers, yarns, and fabrics must be used in these new products. However, the major part of the traditional textile industry plays no role in the new developments; it only acts as suppliers of platforms.
- A lack of understanding in fundamental textiles often result in E-textiles that though functionally sophisticated often exhibit significant deviation from the intimate nature of textiles particularly the touch and feel of textiles that cannot be replicated by any programmed materials including shape-memory substances. The assumption that a sensor can also feel is a gross assumption that must be seriously examined in the development of E-textiles.
- As exciting as the E-textile field may seem, its market growth is hindered by many constraints. Indeed, one of the main reasons that this market is quite unpredictable stems from the fact that it is populated largely by small businesses or initiated at university spin-offs. In addition, only time will prove whether substances such as polymeric-based conductors or shape-memory polymers are sustainable in terms of their efficiency and performance over time and more seriously in their impact on the environment upon discard.
- Price can be a major obstacle against a growth that must be based on justifying the significant capital investment and the R&D cost of E-textiles.

Against the earlier concerns, one can list many driving forces for a growing market in E-textiles. These include the following:

- The increasing regulations by governments around the world that are associated with many products such as medical, fire retardant, stain resistant, and military clothing are likely to drive the market of E-textiles upstream. This driving force may also present challenges not only in the product development aspect but also in the cost aspect. Over the years, the traditional textile industry has been accustomed to regulations associated with trade and safety, yet the industry has been able to accommodate these regulations. The regulations associated with E-textiles in sensitive fields may reach a point where some products may not be sold over the counter. The point here is that a risk associated with a passive traditional textile product is far less than a risk associated with an active or reactive life-controlling E-textile (e.g., fitness trackers, posture warning systems, and heart-rate systems).
- The market of E-textiles will inevitably shift from small business developers to government-sponsored developers. This will be particularly true for high-risk developments.
- The issue of price will eventually fade away by the economics of scale.

14.2.4 Key challenges in the design of E-textiles

The design analysis of E-textiles is highly complex and significantly sophisticated. Details of this type of analysis are outside the scope of this chapter as they require much larger space and more expert inputs. In this section, some of the design challenges of E-textiles are presented. These challenges can be divided into textile challenges and E-challenges. Textile challenges related to E-textiles can be divided into two categories: traditional challenges and specific challenges. Traditional challenges include the choice of appropriate fibrous materials suitable for the specific performance characteristics of E-textiles. As clearly indicated in the earlier sections, the compatibility between fibrous and nonfibrous materials (e.g., conductive polymers, electronic elements, or alloys) represents a critical aspect in the design of E-textiles. This means that key parameters such as fiber type, yarn structure, and fabric construction must be carefully selected in view of the anticipated performance of E-textiles. Performance characteristics that are not directly related to the functional performance of an E-textile must also be highly considered in the design process. These include durability against tear, bursting, wear, etc. Certainly, the cost added by the choice of one fibrous assembly or external substance must be considered in reference to the added value of the product and the market price accommodation.

The E-challenges are also enormous. Special computation models must be developed depending on the specific application of E-textiles. These models must be reliable within the product's functionality and predetermined constraints. In addition, the outputs of the relationships introduced by these models must be predictable not only from a designer's viewpoint but also more seriously from a user's viewpoint. In traditional textiles, this challenge is overcome by expected interference of the user when situations warrant this interference (e.g., wearing different or multiple-layer clothing to meet changing climate conditions). E-textiles, on the other hand, must make this adjustment automatically and without user's inputs. Electronic sensors embedded in textile fabrics must be adaptable and reconfigurable to changing utilization conditions (e.g., environmental changes, energy shortage, battery lifetime, circuit durability, and fabric durability). The dynamic nature of these changes represents a true functionality test of E-textiles. Fabrication of E-textiles can be a true challenge given the need for new manufacturing technologies that are not only capable of product assembly but also more seriously of maintaining the inherent flexibility of yarns and fabrics equipped with electronic devices. In addition, the reliability of E-textiles will largely depend on energy storage capability and unconventional power sources that can be embedded into yarns or fabrics.

One approach to the design of E-textiles is shown in Fig. 14.1. Depending on the application intended for an E-textile product, performance characteristics are determined. These characteristics lead to establishing different attributes of fibrous materials and nonfibrous components (e.g., conductive polymers, alloys, composites, and electronic elements). The performance characteristics are then transformed into a fibrous assembly and an electronic architecture. The fibrous assembly implies fiber type, yarn structure, fabric construction, and garment assembly. The electronic

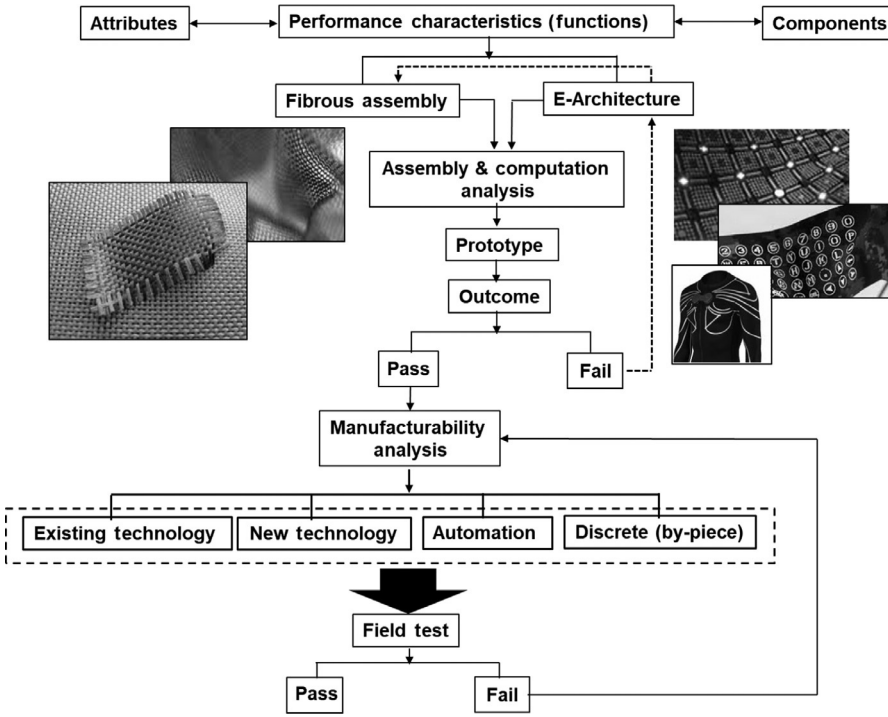


Fig. 14.1 General design scheme of E-textiles.

architecture describes the set of software and hardware required to meet the intended performance and their interaction in forming a computer system or electronic platform. It also describes the methods of positioning electronics or depositing smart materials into the fibrous assembly. Furthermore, it describes energy requirements, power sources, and energy storage capabilities. In the design context, fibrous assembly and electronic architecture represent design constraints that must be met to move forward with the design project. Therefore, they require assembly and computation analysis that can lead to a design prototype. Previous aspects of design conceptualization discussed in Chapters 4 and 5 and the backward design analysis discussed in Chapter 12 are all applicable in this phase of design. The assembly and computation analysis should lead to a prototype that can be tested to validate its adherence to the intended performance characteristics. Advanced tools such as 3D printing and digital knitting should be considered in the development of prototypes. At this point, a prototype may fail or pass the required specifications. A functionality failure will lead to revisiting the phase of fibrous assembly and electronic architecture. A functionality success will lead to the next phase, which is manufacturability analysis. This is a critical phase that can make or break any development

of E-textiles as many options must be evaluated including (a) making use of existing manufacturing technology (cost-saving), (b) developing new manufacturing technology (high cost), (c) automation, and (d) discrete manufacturing. A field test of the manufactured product will also represent a critical phase. Important approaches discussed in Chapter 6 such as design thinking, lean startup design, and minimum viable product (MVP) should be entertained in the transformation process from prototype to mass manufacturing. These approaches are critical in the design of E-textiles because of the high cost associated with the developments of these products. The operational longevity of E-textiles is also a critical performance characteristic. This means that the product should be defect free or of high fault tolerance, and it should be robust against possible malfunctioning. More importantly, computational ability must accommodate changing external conditions at the highest efficiency possible.

From an E-prospective, Marculescu et al. [34] (a group of scientists of electrical and computer engineering of Carnegie Mellon University) described some of the limitations in the design of E-textiles in a 2002 article as follows: "E-textiles are not classic data networks. While the underlying structure of an e-textile application implies the existence of many processing elements, connected in a Textile-Area Network (TAN), they have limited processing and storage capabilities, as well as very limited power consumption budgets. Hence, classic techniques and inherent methodologies for coping with mapping an application, communication among nodes and dealing with network failures (including congestion), are not appropriate. In addition, having very limited processing capabilities, e-textiles are not the equivalent of desktops/laptops on a fabric, restricting significantly the range of applications that can be mapped on them." In the same article, the authors suggested the development of a methodology for modeling analysis and middleware support for E-textiles that included (1) modeling of colloidal computing in which simple computation particles are dispersed in a communication medium that is inexpensive, possibly unreliable, yet sufficiently fast; (2) an analytical and simulation-based framework that allows to explore the design space early on for energy/performance/fault-tolerance trade-offs leading to designs that are feasible and easily adaptable to the application profile; and (3) a Port-Based Adaptable Component Architecture (PBACA) that allows every computational node to reconfigure its computation and communication with other nodes, in real-time.

In view of the earlier aspects, design conceptualization of E-textiles must lead to reliable performance-attribute relationships that will depend on the specific application considered. This task cannot be achieved by electrical and computer engineering only, and it certainly cannot be achieved by textile or material engineers only. A joint effort is necessary for reaching optimum performance of E-textiles. The framework of this effort can be stemmed from the design aspects discussed in Chapters 4–6. The backward projection analysis and the performance-attribute diagrams discussed in Chapter 12 are far more critical in E-textiles than traditional textiles. Fig. 14.2 illustrates a list of examples of performance characteristics and related attributes for E-textiles.

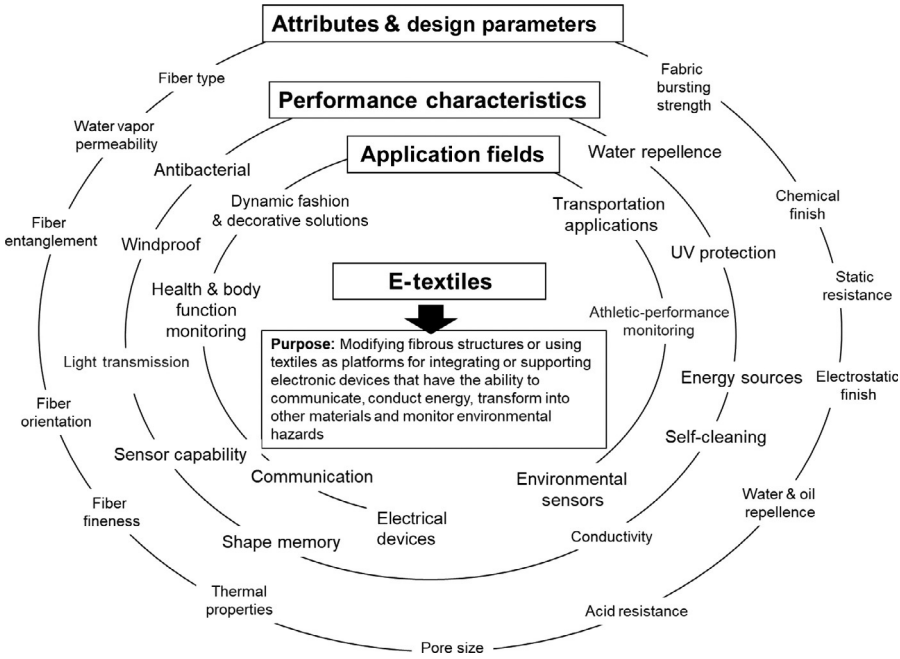


Fig. 14.2 Performance characteristics and related attributes of fibrous products used in E-textiles.

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Performance characteristics of technical textiles: Part II: Transportation textiles

15

15.1 Introduction

The relationship between textiles and transportation applications can be traced back to the earliest form of transportation in history. The ancient Egyptians wove sails from animal skins and bundles of papyrus reeds tied together. The Phoenicians wove sails from a variety of fibers, such as hemp, flax, ramie, and jute. The victory of the racing yacht America in 1851 crowned cotton fibers as the sailing material supreme. Later, sailing cloth was made of all types of synthetic fibers including nylon, polyester, aramids, and carbon fibers and in a variety of woven, spun, and molded textiles. Designers of sailing cloth were the first to realize the technical aspects of textiles thousands of years before the term technical textiles was coined. They realized that high sailing performance requires optimum levels of key attributes such as high initial modulus to resist stretching, particularly for upwind sails, low creep, UV resistance, and high flex strength.

In ground and air transportation, textiles began their journey largely as a non-technical product used for interior and seating purposes. Early design engineers of cars and airplanes did not realize the critical importance of textiles; they only trusted that fabrics used as interiors will perform their expected functions and that suppliers of these fabric would know better about what materials to supply. On the other hand, the traditional textile industry did not fully realize that fabrics used for transportation purpose should be designed in accordance to technical specifications except perhaps for safety and strength measures. Performance characteristics such as high abrasion resistance, light fastness, stain resistance, and thermal comfort were not part of the specifications of the early textiles used in ground and air transportation, and the technology was not fully there to enhance these characteristics. These practices continued until perhaps the mid-1970s (the oil crisis time) when consumers and regulations began to impose more performance characteristics including fuel efficiency, light weight, and high durability. This has led to more integrated designs of transportation means. The transition from the product-focus era to the consumer-focus era discussed in Chapter 2 has added many more demands including style and attractiveness of interiors; higher safety measures (seat belts and airbags); lighter weight for fuel efficiency; and more integrated durability concepts including strength, flexibility, stain resistance, dirt resistance, UV resistance, aesthetics, and comfort.

The term ground transportation can be used to imply transportation vehicles such as automobiles, buses, trucks, and trains or to cover materials used for building highways and railroads. The most dominant ground transportation vehicles are passenger

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automobiles. Depending on the source of statistics, estimates range from 1.2 to 1.6 billion vehicles running on the world's highways today, and it may reach well above 2.5 billion by 2050. In 2016, the number of passenger cars produced worldwide exceeded 73 million. This is a 75% increase since 2000 (https://www.worldometers.info/cars/). If this trend continues, the world will be producing more than 100 million passenger cars annually by 2030. Since fuel efficiency has been and will always remain a critical performance criterion, engineering design has focused for many years on designing fuel-efficient vehicles. This has been a classic design problem in which material selection has played a central role through developing new auto-body materials, discovering new energy sources, or both. The selection of appropriate materials for automobiles has been an evolutionary process of great interest. For many years, the competition between steel and aluminum has been well documented [1–3]. Now, traditional metals are being replaced by other materials including lighter metallic alloys, nonmetals, and fiber composites.

From a product development perspective, the battle between aluminum and steel in building automobiles is worth noting. Aluminum is typically one-third less dense than steel, and this makes it a serious competitor in many automobile parts including doors, hoods, trunk decks, and roofs (collectively make up more than 60% of a vehicle's weight). Using aluminum alloys, yield strength equal to that of moderately strong steel can be reached (similar resistance in fender dent). The problem, however, is that alloying of aluminum does not significantly affect its elastic modulus, which is one-third of that of steel [3]. Good elastic modulus will prevent automotive door panels or hood from being easily and largely deflected by external stresses. Early thoughts to resolve this performance issue was through increasing the thickness of aluminum alloys to three times that of the steel. Obviously, this would have defeated the whole purpose of the substitution as it would have resulted in a substantial weight increase equal to that of steel. This design problem resulted in extensive research by two British material scientists Michael Ashby and David Jones, in the 1980s in which the way components actually deflect was taken into consideration and the result was to increase the thickness of the aluminum of panel doors only slightly to reach equivalent performance [4]. Accordingly, through understanding of the relationship between material properties and structural design, a compromise was made in which the net result was a 33% weight saving due to the substitution of aluminum for steel on such body components.

Another more recent evolution in automobile design was the use of polymeric materials driven by the need for further reduction in automobile weight. In general, plastics are one-sixth the weight of steel and one-half that of aluminum per unit volume [5]. As expected, polymeric materials had a tougher task in competing against metals in this very profitable application. In general, the strength of most plastics (e.g., epoxies and polyesters) is roughly one-fifth that of steel or aluminum, and their elastic modulus is one-sixtieth that of steel and one-twentieth that of aluminum [5]. As a result, the only way for polymeric material to be a part of the automobile body was through composite structures. In this regard, the key factor was to combine relatively weak and low-stiffness resins with high-strength, high-modulus reinforcements. As it is always the case, cost consideration was an issue in using composite structures,

and compromises had to be made. For example, the use of carbon fiber (five times the modulus of steel) is of relatively high cost that limited their use in automobiles and moved them further to the aerospace industry where the high cost can be justified. Other options that have been entertained included glass fibers (1.5 the modulus of aluminum) and mixtures of glass and carbon fibers. Now, the use of composite structures in automobiles has become an accepted reality, a long road that had begun in 1953 with the introduction of fiberglass-reinforced plastic skins on General Motors' l953 Corvette sports and continued until today. In 1984, General Motors' Fiero was introduced to the market with the entire body made from composites. Now, composites represent the dominant material in automobiles.

As indicated earlier, strives for ever-increasing fuel efficiency have never ceased. Now, hyper vehicles are available with weights less than half of that of conventional cars. This is certainly creating a radical "dematerialization" in the auto industry. Some hyper vehicles use about 92% less iron and steel than conventional cars. Indeed, the only type of metals that will increase in consumption as a result of this type of cars will be copper material used for electric drives. In 2007, the US President signed a bill, approved overwhelmingly by the House of Representatives raising automotive fuel economy standards for the first time in more than three decades, requiring a corporate average of 35 miles per gallon by 2020. This bill also boosted federal support for alternative fuel research and energy conservation efforts. These thresholds were later increased to 41.7 miles per gallon for passenger cars and 31.3 miles per gallon for light trucks. These are all indications of responding to consumer's need for fuel-efficient vehicles and even more seriously for lower environmental risk. They also represent opportunities for further developments in energy saving and alternative energy sources in which fiber and polymer engineers should be highly considered.

Figs. 15.1 and 15.2 illustrate examples of fibrous components that are used in automobiles and aircrafts, respectively. Fibers used in transportation applications can be natural or synthetic; yarns can be spun, continuous filament, texturized, or compound core/sheath; and fabrics can also be of all styles including narrow fabrics, wide fabrics, woven, knit, nonwoven, suede, pile, and raised. Transportation applications also open the door for more use of fiber composites due to the need for light weight, high durability, and fuel economy.

In the following sections, examples of technical textiles used in different vehicle components will be briefly discussed with a great deal of emphasis on performance characteristics and design aspects. These include air bags, seatbelts, and seats. Again, this discussion should not be considered as a comprehensive coverage of these products as many references devoted to this subject are now available [1,2,3–10].

15.2 Developments of safety airbags

An airbag is an inflatable cushion designed to protect vehicle occupants from serious injuries in the incidents of crashes or serious collisions. It is only one component of an inflatable restraint system, also known as an air cushion restraint system (ACRS) or an airbag supplemental restraint system (SRS). Following the basic steps of product

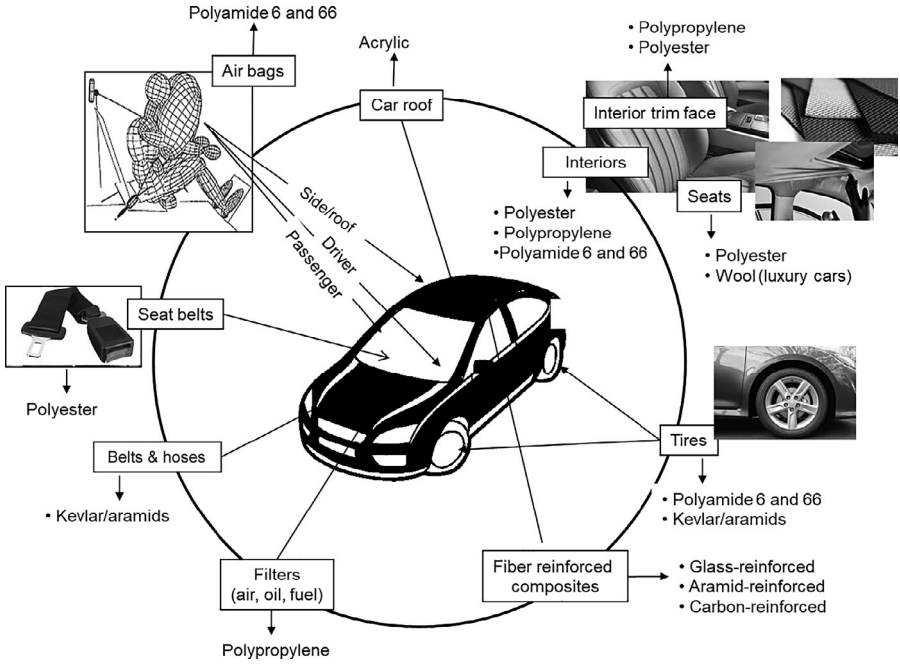


Fig. 15.1 Examples of fibrous components used in transportation vehicles.

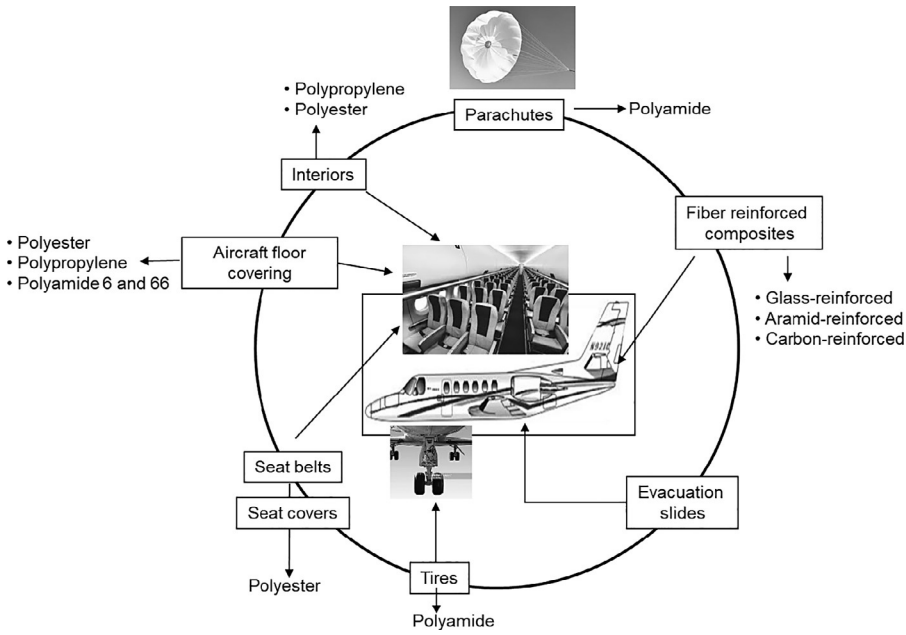


Fig. 15.2 Examples of fibrous components used in aircrafts.

development discussed in Chapter 3 (Fig. 3.1), an idea of a new airbag fabric system or a modified version of an existing system should primarily stem from a good realization of the relationships between the desired performance characteristics of an airbag and the attributes of the various components forming the airbag system. These relationships should be based on good knowledge of the airbag system. In this regard, three design aspects associated with airbags should be addressed [8–10]: (1) basic components of an airbag system, (2) the deployment mechanism, and (3) safety-related issues. These aspects are discussed later.

15.2.1 Basic components of an airbag system

An airbag module has three main parts (see Fig. 15.3): the airbag, the inflator, and the propellant. The airbag fabric is basically a woven construction that can be made in different shapes and sizes depending on specific vehicle requirements. The inflator canister or body is commonly made from either stamped stainless steel or cast aluminum. Inside the inflator canister is a filter assembly commonly consisting of stainless steel wire mesh with ceramic material sandwiched in between. When the inflator is assembled, the filter assembly is surrounded by metal foil to maintain a seal that prevents propellant contamination. The propellant, in the form of black pellets, is conventionally sodium azide (inorganic compound, NaN_3) combined with an oxidizer and is typically located inside the inflator canister between the filter assembly and the initiator [6–8].

The conventional manufacturing process used for making airbag module consists of three different separate assemblies (Fig. 15.3B): (1) propellant manufacturing, (2) inflator components assembly, and (3) airbag cutting and sewing. These operations can be performed in three different manufacturing sites to produce the components that can be assembled later into a complete airbag module. As indicated earlier, the conventional propellant consists of sodium azide mixed together with an oxidizer, a substance that helps the sodium azide to burn when ignited. The sodium azide is received from outside vendors and inspected to make sure it conforms to requirements. After inspection, it is placed in a safe storage place until needed. At the same time, the oxidizer is received from outside vendors, inspected, and stored. Different manufacturers use different oxidizers, which may be copper oxide or iron oxide. Although sodium azide is quite toxic, manufacturers' tests show that it is consumed entirely in the reaction and converted to harmless substances. From storage, the sodium azide and the oxidizer are then carefully blended under sophisticated computerized process control. Because of the possibility of explosion, the powder processing takes place in isolated bunkers. Production occurs in several redundant smaller facilities so that if an accident occurred, production would not be shut down, only decreased. After blending, the propellant mixture is sent to storage. Presses are then used to compress the propellant mixture into disk or pellet form.

Inflator components are the metal canister, the filter assembly, and initiator (or igniter). These components are also manufactured separately and inspected prior to the final assembly using an automated production line [2,7,8]. The final assembly consists of the inflator components combined with the propellant. Laser welding

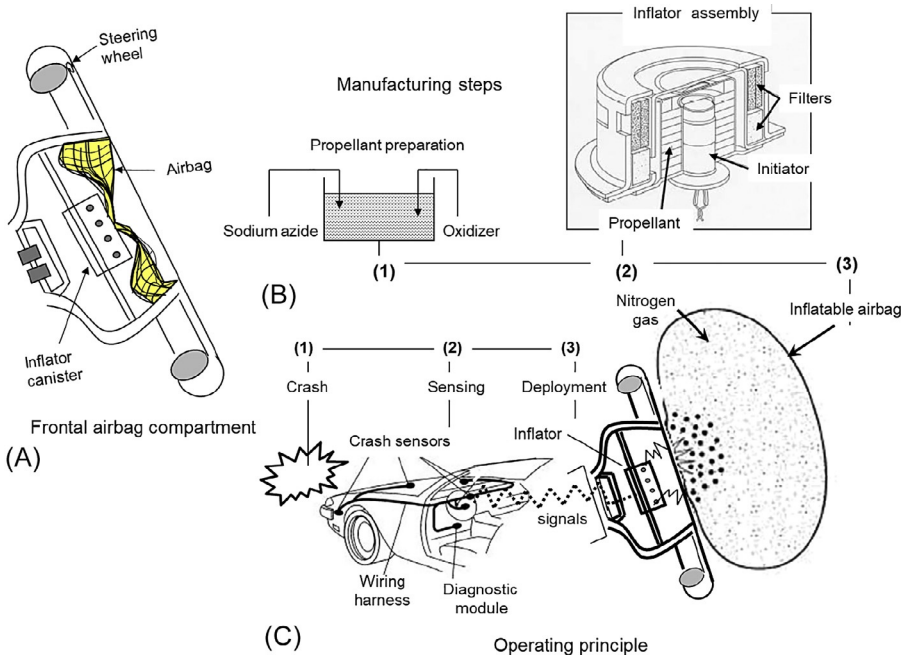


Fig. 15.3 Basic components of airbag (schematics assembled from different auto-maker sources).

(using CO_2 gas) is used to join stainless steel inflator subassemblies, while friction inertial welding is used to join aluminum inflator subassemblies. Friction inertial welding involves rubbing two metals together until the surfaces become hot enough to join. The inflator assembly is then tested and sent to storage until needed.

The airbag woven fabric is normally manufactured in an independent weaving facility. It is then inspected carefully, die cut to the appropriate shape, and sewn both internally and externally to join its sides. The normal design of the driver's airbag is two circular pieces of fabric sewn together [8,10]. The passenger bag is teardrop shaped, made from two vertical sections and a main horizontal panel. The sewing thread is to be chosen properly; nylon 66, polyester, and aramid fibers can be used for sewing. When sewn, it is folded inside its cover like a parachute with extreme care to ensure smooth deployment. These folds are of various types including [7,8] accordion folds, reversed accordion folds, pleated accordion folds, and overlapped folds. After sewing, tests are performed to check for leak and seam imperfections. The airbag is then mounted to the tested inflator assembly, folded, and secured with a breakaway plastic horn pad cover. In addition to the basic airbag module components discussed earlier, other components such as crash sensors, diagnostic monitoring units, steering wheel connecting coils, and indicator lamps are combined with the airbag module during vehicle assembly [9,10]. All the components are connected via a wiring harness as shown in Fig. 15.3C.

The performance of an airbag may vary depending on its location in a car. In this regard, the size of an airbag is a key design parameter. The driver and the passenger airbags are designed to protect against frontal collisions. Typically, the driver airbag module is located in the steering wheel hub, and the passenger airbag module is located in the instrument panel. When fully inflated, the driver airbag is approximately the diameter of a large beach ball. The passenger airbag can be two to three times larger since the distance between the right-front passenger and the instrument panel is normally greater than the distance between the driver and the steering wheel. New cars are also equipped with side airbags to protect against moderate to severe side impact crashes. These airbags are generally located in the outboard edge of the seat back, in the door, or in the roof rail above the door. Seat and door-mounted airbags all provide upper body protection. Some airbags also extend upward to provide head protection. Two types of side airbags, known as inflatable tubular structures and inflatable curtains, are specifically designed to reduce the risk of head injury and/or help keep the head and upper body inside the vehicle [9]. These airbags are claimed to reduce injuries and ejection from the vehicle in rollover crashes. Side airbags are typically smaller in size than front airbags, and they deploy more rapidly.

15.2.2 Airbag deployment mechanism

An airbag can certainly be considered as a model of a smart system [8,9]. At the incident of vehicle's crash, the frontal crash sensor is activated sending an impulse to the diagnostic unit. This unit evaluates the strength of the input signal and triggers an electric impulse of similar strength, which causes the central igniter inside the airbag to fire. Igniter fire penetrates the propellant chamber; this ignites the propellant and produces and expels hot gas (e.g., nitrogen gas, comprising 78% ambient air). This gas passes through a filter and enters the system's bag through inflator ports to inflate the airbag. This entire process occurs in a fraction of a second (i.e., within 0.06 s).

In principle, the impact of a collision process can be described using the Newton's laws that indicate that "a body in motion will stay in motion until it is acted upon by an outside force." Travelers driving vehicles may be driving within city limits at low speeds or on highways at very high speeds. In either situation, the driver does not typically feel that his/her body is moving at the same speed as that of the vehicle. Only when a sudden brake is taken, or in the event of a crash, that the occupant of a vehicle feels the speed almost at an equal rate as the original speed of the vehicle. The problem here is that such a sense is not only a mental one but also more seriously a physical one, as the body reacts to the sudden stop or crash by a fast movement that in many situations can result in an occupant flying out of the seat, if not restrained by a seat belt. This is a body movement of a momentum that is equivalent to the initial speed of the vehicle.

The earlier illustration clearly alludes to two critical aspects of safety for vehicle occupants: body movement during a crash and possible injuries resulting from this movement. In response to these two aspects, an occupant will need a restrain from movement and a restrain from impact (or a cushion against sharp objects). The former is achieved by the car safety seatbelt, and the latter is achieved by the safety airbag,

which not only prevents the impact but also distributes the impact force over a larger body area.

In view of the earlier points, the design of an airbag system must account for three consecutive mechanisms of airbag deployment [8]: significant impact (crash), sensing, and deployment. Under a severe frontal crash, crash sensors send a signal to the inflator unit within the airbag module. An igniter starts a reaction, which produces a gas to fill the airbag, making the airbag deploy through the module cover. Some airbag technologies use nitrogen gas to fill the airbag, while others may use argon gas. The gases used to fill airbags are supposedly harmless. The time duration from the onset of the crash to the entire deployment and inflation process is only about 1/20 of a second. This is an essential requirement since a vehicle changes speed so fast in a crash. As the occupant contacts the bag, deflation begins immediately, and the gas escapes through pores in the fabric. The bag is fully inflated for only one-tenth (1/10) of a second and is nearly deflated by three-tenths (3/10) of a second after impact. Talcum powder or corn starch is used to line the inside of the airbag and is released from the airbag as it is opened. Once deployed, the airbag cannot be reused and should be replaced by an authorized service department.

Crash sensors located in the front of the vehicle or in the passenger compartment are typically activated by forces generated at the moment of crash impact. They measure deceleration, which is the rate at which the vehicle slows down [9]. Accordingly, the vehicle speed at which the sensors activate the airbag varies with the nature of the crash. It is important to point out that airbags are not designed to activate during a sudden brake or on rough or bumpy road. Indeed, the maximum deceleration generated in the severest braking is only a small fraction of that necessary to activate the airbag system. The diagnostic unit detects the severity of the impact and transmits the signal to the airbag activation system. This unit is always activated when the vehicle's ignition is turned on. It also detects any defect in the airbag system and gives a warning light to alert the driver for the need for system examination and repair. Most diagnostic units contain a device, which stores enough electrical energy to deploy the airbag if the vehicle's battery is destroyed very early in a crash sequence.

The variable nature of a car crash adds to the complexity of the design of crash sensors. Some estimates a near frontal and a frontal collision to be comparable with hitting a solid barrier at approximately 8–14 miles per hour (mph). These estimates are obtained from laboratory testing or individual road incidents, and they may not reflect the true impact of some crashes [10,11]. The variability of a car crash impact will depend on many factors including the size of the car involved in the crash, the relative speed between a striking and struck vehicle, the collision angle, and the distribution of crash forces across the front of the vehicle. The speeds and pressures developed in airbag deployment are difficult to measure [8,9]; some popularly quoted values for airbag deployment speed are in the order of 400 mph (over 640 kph), and internal cushion pressures regularly rise above 100 kPa. In addition to these substantial mechanical stresses, the airbag cushion may also be exposed to high temperatures from inflation gases and explosive pressure. Temperatures of up to 5000°F (or over 2700°C) have been cited in technical literature [8,9].

15.2.3 Safety-related concerns of airbags

As indicated in Chapters 4 and 5, a product model (prototype) is typically a result of a design analysis that aims at providing the best compromising solution and not necessarily the best optimum solution. Airbags being liability products must deviate from this common goal and reach the most possible optimum solution. The initial design of airbags was primarily focused on the deployment mechanism with the key parameters being appropriate material, accurate and reliable sensors, timely deployment, timely deflation, and safety measures against explosion. These are largely deterministic features that can be optimized by a joint effort of skilled design engineers in different disciplines including textile, material, mechanical, chemical, and electrical engineering. Because of these significant efforts, cars are now much safer than ever; fatality rates from car accidents are dropping every year, and it is not uncommon for many vehicles to earn top safety ratings from the federal government's crash test program or the one sponsored by the Insurance Institute for Highway Safety (IIHS). According to the National Highway Traffic Safety Administration (NHTSA) 2015 statistics, frontal airbags reduced driver fatalities by 29% and by up to 32% in the age group of 13 and older.

Some of the safety-related issues associated with airbags that were realized in the initial testing phase included the release of dustlike particles in the vehicle's interior during deployment. Most of this dust consisted of cornstarch or talcum powder, which were used to lubricate the airbag during deployment. Small amounts of sodium hydroxide may initially be present. This chemical can cause minor irritation to the eyes and/or open wounds; however, with exposure to air, it quickly turns into sodium bicarbonate (common baking soda). Depending on the type of airbag system, potassium chloride (a table salt substitute) may also be present. For most people, the only effect the dust may produce is some minor irritation of the throat and eyes. Generally, minor irritations only occur when the occupant remains in the vehicle for many minutes with the windows closed and at no ventilation. However, some people with asthma may develop an asthmatic attack from inhaling the dust.

Other problematic issues that were raised in the initial design represented common aspects that are typically handled in the design conceptualization phase of a product through reliable statements of broad and specific problem definitions. For example, the considerable inflation force of the airbag. This high impact force was found to cause injuries to some car occupants. However, the initial realization was that these contact injuries, when they occur, are typically very minor abrasions or light burns and they should be considered as insignificant effects in view of the obvious merits of an airbag. Another issue was the choice of raw materials, particularly the fiber type, and the seaming characteristics. These are all safety-related issues as an inappropriate material may not deploy properly particularly after a long storage and in different environments. Seam quality is also critical in connection with the overall integrity of an airbag during deployment and in the storage state.

Unfortunately, relying completely on deterministic design analysis often leads to overlooking variable aspects that though not directly related to functional performance, it can impact the overall performance of a product. Airbags were designed

to be defect free and malfunction robust but did not accommodate all variable human-related aspects. For example, air bags were designed to work with seat belts, not replace them, yet the performance of an airbag in the absence of a seatbelt use was not fully considered in the design-problem model of airbags. This leads to an open-ended question in the case of fatality of whether it was caused by the failure to use a seatbelt or due to the impact of airbag deployment, particularly on young children or older passengers. The various seating habits of passengers were also not considered in the design of airbags. These variables call for a "probabilistic design" of extremely high intelligence. This should be quite possible in the era of big data and self-driven vehicles. Including human-related aspects will obviously add a critical dimension to the overall design analysis by virtue of the variable modes of human body/airbag interaction.

Essentially, an airbag acts as a cushion against body impact. However, in order for an airbag to assume this function, it must inflate rapidly and at high impact. In an unstrained (no-seatbelt) situation, the faster the body momentum at the time of crash, the greater the impact of the airbag against the body. The combination of body momentum and airbag strike can indeed cause injuries to the occupant. The complexity of this combination stems from the multiplicity of variables that can result in a wide range of injuries from a mild one to a fatal one. Investigations of this matter revealed that most airbag injuries resulted from occupants being too close to or in direct contact with an airbag module when the airbag deploys [11]. Some injuries may be sustained by unconscious drivers who are slumped over the steering wheel, unrestrained, or improperly restrained who slide forward the seat during precrash braking. Objects attached to or near an airbag module can also be propelled with great force against the occupant body during airbag deployment. Currently, most of these safety issues problems are handled through regulations and not design efforts.

The National Highway Traffic Safety Administration (NHTSA) recommended that drivers sit with at least 10 in. between the center of their breastbone and the center of the steering wheel and children 12 and under should always ride properly restrained in a rear seat. In addition, safety belts should always be worn with the lap belt low and snug across the hips and the shoulder belt across the chest. Shoulder belts should never be placed under the arm or behind the back. Front seat drivers and passengers should sit upright against the back of the seat. Finally, drivers should adjust the seat such that they position themselves away from the airbag module while maintaining the ability to safely operate all vehicle controls. In recent years, the option of deactivating an airbag (by switching it on or off) was given to drivers by NHTSA. This was an interesting regulatory rule that assumed that some drivers can make appropriate decisions on whether an airbag is suitable for their safety. This rule was made based on three conditions: (a) occupants with medical conditions that place them at specific risk, (b) occupants who cannot adjust their driver's position to keep at least 10 in. from the steering wheel, and (c) occupants who cannot avoid situations that require a child 12 or under to ride in the front seat.

It is very possible that the market will not see an airbag design that can substitute for these regulations and for the lack of follow-direction by many users. But a progress in this direction will certainly revolutionize this critical market. Many automobile

companies are continuously working on this issue and in different directions including the following:

- Airbags that exhibit gentler inflation and less abrasive fabric material.
- Smart airbag that has the ability to sense the size and weight of the seat occupant or even if the seat is unoccupied and deploy accordingly.
- Outward-deploying airbags (from the seat belt).
- A hybrid inflator that uses a combination of pressurized inert gas (argon) and heat from a propellant to significantly expand the gas' volume. This system would have a cost advantage, since less propellant could be used.
- Elimination of sodium azide propellant (toxic in its undeployed form). Pyrotechnic inflation technology has changed over the past few years from reliance on sodium azide to the use of organic propellants to minimize environmental impact of the propellant and increase efficiency.
- Appropriate airbag fabric coating or uncoated airbags.
- The use of energy absorbing material such as polyurethane foam and polypropylene foam with optimum properties for the absorption of impact energy in surface vehicle interior.

15.2.4 Design aspects of safety airbags

The earlier information shed a great deal of light on the basic performance characteristics of an automotive airbag. From a design viewpoint, this product provides a unique opportunity for engineers of different disciplines to work together and exchange ideas and thoughts on the best way possible to develop an airbag that can operate reliably in the event of crashes through understanding the principle of the deployment mechanism and the different safety considerations discussed earlier. The interdisciplinary aspect of this development is a result of the fact that this product consists of different types of materials including fibers, polymers, chemicals, stainless steel, and cast aluminum. In addition, it requires electrical and computer engineers for the design of sensors and diagnostic units, mechanical engineers for the design of deployment mechanism, polymer and fiber engineers for the design of airbag fabric, and chemical engineers for the design of gas and chemical flow systems. In all situations, it will be important to account for probabilistic design aspects associated with human interaction with airbags and seatbelt systems. Our discussion on the design aspect will be limited to fabric engineering for airbag module.

15.2.4.1 Performance characteristics of fabrics used in airbag systems

The design of a suitable fabric for airbag systems represents the most critical phase in the development of airbag module. This is because fabric is the primary component that comes in direct contact with the vehicle occupant at the time of crash; all other components work to support this immediate contact. The great flexibility associated with fabric design and raw material selection has made it common among many airbag design engineers to believe that it is far easier and less costly to adjust the bag and fabric to meet the needs of a particular inflator than to develop mechanisms and

inflation processes that are fabric-friendly. The primary performance characteristics of the fabric component of an airbag module should be as follows (see Fig. 15.4):

- The ability to withstand the force of the hot propellant chemicals used in the inflation
- The ability to allow gas release and disallow any penetration of chemicals through the fabric that could burn the skin of the car occupant
- The ability to fold and unfold easily, particularly after a long storage period
- The ability to provide a brief cushioning effect on the occupant in the event of a crash

The earlier performance characteristics can be translated into the following material attributes:

- The first performance characteristic implies the need for fabric of high tear strength, high tenacity, and high toughness. In addition, the resistance of sudden energy during airbag deployment requires a material that can withstand high temperatures from inflation.
- The second performance characteristic implies a closed fabric construction, optimum permeability, optimum blocking, and high antiseam slippage (in the case of fabrics with seams).
- The third performance characteristic implies light weight, high flexibility, and high aging stability.
- The fourth performance characteristic implies a smooth and soft surface.

Optimum levels of these attributes can be met using a design cycle that begins with the appropriate fibers and end with the appropriate fabric. Some of the relevant attributes

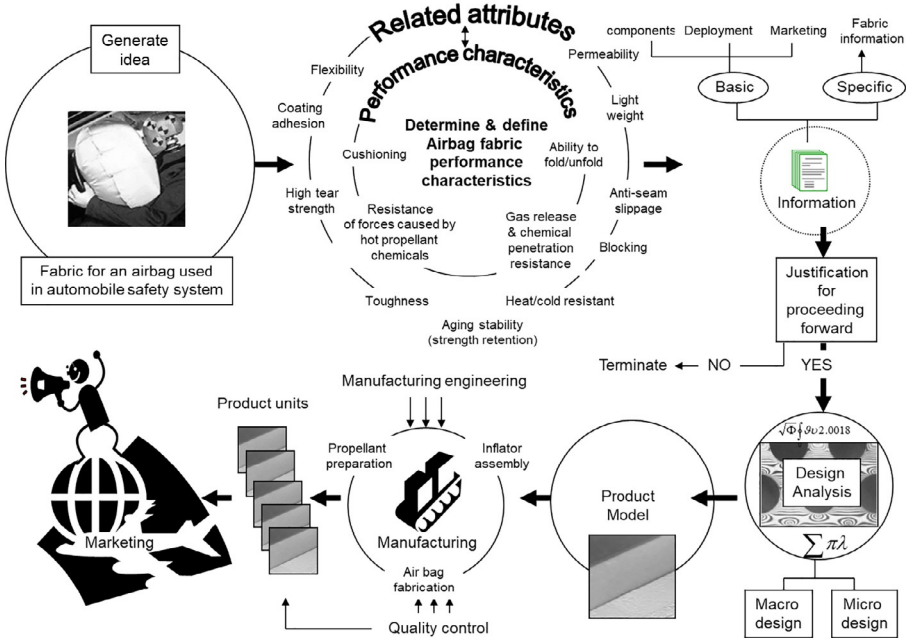


Fig. 15.4 Basic steps of airbag development.

of fibers and fibrous assemblies used in airbag systems are shown in Fig. 15.4. These are discussed in the following sections.

15.2.4.2 Fiber selection for safety airbags

One of the critical design aspects of air bags is "aging." An airbag may be stored folded in a vehicle airbag compartment for many years without deployment; yet, it is expected to deploy reliably and immediately at the time of crash and overcome the mechanical stresses imposed by the rapid inflation process. Prior to the time of use, an airbag could be exposed to extremes of temperature and humidity over a significant period. These factors can significantly influence the strength retention of fabrics. A substantial reduction in strength retention over time can result in a failure in airbag deployment. It is important, therefore, to select a fiber with high strength retention over time.

The two primary fiber candidates that have been examined for airbags are polyester and polyamide fibers. Within the polyamide fiber category, nylon 66 is the most commonly used fiber in airbag fabric, but nylon 6 has been examined for special uses. Experimental comparative analysis of fibers suitable for airbags [12,13] revealed that nylon 66 has superior strength retention over polyester fiber over time at temperature of 85°C and relative humidity of 95%. These results are shown in Fig. 15.5. According to DuPont, these results were also supported by extensive testing under simulated vehicle lifetime aging cycles in laboratory conditions and real-life observations over many years. Nylon 66 was also found to be superior to polyester fibers in many of the

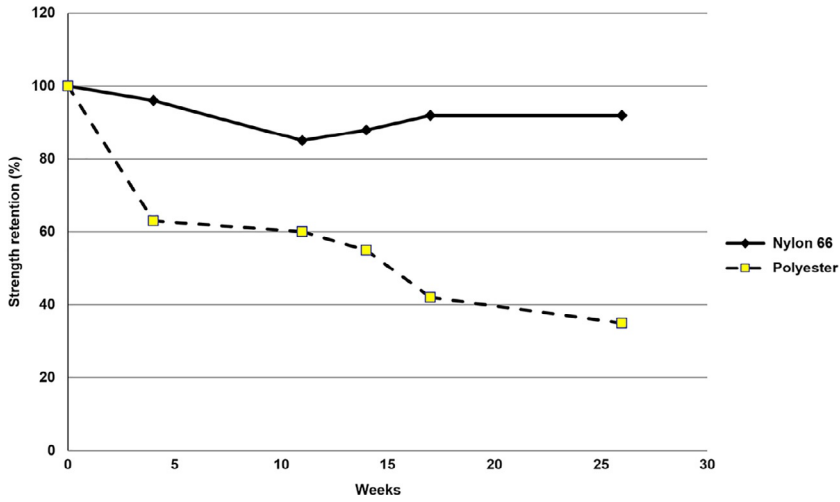


Fig. 15.5 Comparison between uncoated nylon 66 and polyester fabric tensile strength retention after aging test.
Modified from DuPont data (DuPont Automotive TI Leaflets H-48030 and H 48032 (USA); DuPont Technical Documents, http://www2.dupont.com/Automotive, 2007).

attributes related to the performance characteristics of safety airbags. Tables 15.1 and 15.2 show a comparison between the values of these attributes reported by DuPont [9]. Note that although nylon 66 and polyester have similar melting points, the large difference in specific heat capacity causes the amount of energy required to melt polyester to be about 30% less than that required to melt nylon 6,6. Some studies [14,15] revealed that in inflation events that use a pyrotechnic or pyrotechnic-containing inflator, cushions made from polyester yarn are far more susceptible to burn or melt through in the body of the cushion or at the seam.

The low bulk density of nylon 66 (1.14 g/cm^3) in comparison with that of polyester fiber (1.39 g/cm^3) represents another advantage in favor of nylon 66. It implies that fabrics of identical yarn and weave structures made from the two fibers will have different weight, with the polyester fabric being about 20% heavier than the nylon 66 fabric. As indicated earlier, a lighter airbag provides many advantages including higher flexibility of folding and unfolding, lower vehicle's weight, and lower kinetic energy of impact on the vehicle's occupant. In addition, the difference in density between the two polymers leads to polyester yarns usually being of higher denier or decitex (weight per unit length) than nylon 66, to generate the same filament diameter. This will result in reduced fabric coverage, higher gas permeability, and weaker seam strength of fabrics made from polyester filaments. According to DuPont, using polyester yarn, the cushion fabric is more open for gas permeation. This reduces thermal protection for the vehicle occupants and makes it more difficult for the cushion designer to control the bag deployment dynamics. In addition, since seam strength

Table 15.1 General comparison between nylon 66 and polyester fibers (DuPont data [12,13]).

Fiber properties	Nylon 66	Polyester
Air permeability	Low	High
Abrasion resistance	High	Low
Thermal resistance	High	Low
Energy absorption	High	Low
Stiffness in cushion	Low	High

Table 15.2 Comparison between nylon 66 and polyester fibers (DuPont data [12,13]).

Fiber properties	Nylon 66	Polyester
Density (g/cm^3)	1.14	1.39
Melting point °C	260	258
Softening point °C	220	220
Specific heat, J/g/°C	1.67	1.30
Specific heat of fusion, J/g	188	117
Total heat to melt, J	587	427
Total heat to soften, J	523	377

is strongly dependent on cover factor, seam performance is negatively impacted. This is particularly important since seam leakage of hot gas is one of the principal concerns in engineering airbags, and the potential for an increase in leakage combined with a reduction in thermal resistance is critical.

Development efforts continue to examine alternative fibers that can provide better airbag performance. The main obstacle against these efforts is cost. Examples of alternative fibers being evaluated include aramid fiber, nylon 4,6, and some modified polyester films. It should also be pointed out that although polyester fiber is not widely used in airbag systems, it occupies over 75% of the market share of fibers used in automotive applications as a result of its dominant use in automotive interiors.

15.2.4.3 Yarns used for safety airbags

In determining the yarn structure suitable for use in airbag fabrics, yarn count represents the most critical design factor. This is because of the well-known effects of yarn count (in denier or dtex) on critical fabric attributes such as fabric strength, elongation, flexibility, weight, and covering power. Yarns used in airbag fabrics are high tenacity continuous multifilaments with counts commonly ranging from 200 to 1000 dtex. The ability to use a certain yarn tex or denier will primarily depend on the denier per filament used. In other words, the key parameter determining yarn count is the filament fineness in dtex or denier. In general, it is desirable to use filaments of low dtex, which can result in finer yarn counts (lighter, flexible, and high covering power fabric) and more filaments per yarn cross section (better control of gas permeability). Table 15.3 lists filament fineness (dtex) and other properties for commercial nylon 66 fibers used in airbag yarns [12,13].

15.2.4.4 Fabrics used for safety airbags

Airbag fabrics are normally tight plain-weave structures of weights ranging from 170 to 220 g/m^2 and thickness from 0.33 to 0.40 mm. These values correspond to fabric specific volume ranging from 1.94 to 1.82 cm^3/g (or fabric density from 0.52 to 0.55 g/cm^3). When nylon 66 fiber is used, the range of fiber fraction of the airbag fabrics will be from 0.45 to 0.48. Corresponding range using polyester fibers in the fabric will be from 0.37 to 0.40. One can see from this comparison that fabrics made from nylon 66 will exhibit higher fiber fraction leading to lower air and gas permeability than fabrics of the same construction made from polyester fibers.

Table 15.3 Typical values of some properties of nylon 66 filaments used in airbag yarns (DuPont Technical Report [12,13]).

Parameter	Typical values
Dtex/filament	2.5–4.2
Tenacity cN/tex	75.0–85
Elongation at break (%)	20–24
Hot air shrinkage (%)	6.0–7.0

The basic construction of airbag fabric will largely depend on the yarn denier used. Common weave constructions used in airbag fabrics include: 840×840 denier filament yarn, 98×98 plain weave, and 60-in. width and 420×420 denier filament yarn, 193×193 plain weave, and 60-in. width. Some passenger airbag fabric of 41×41 plain weave may be made from 630 denier nylon 66 yarn, while a 49×49 plain-weave is typically made from 420 denier nylon 66 yarn.

The airbag fabric is not dyed, but it must be scoured to remove impurities. In addition, coating of airbag fabric is a critical design factor, particularly in relation to fabric protection and permeability aspects. In this regard, developments have been made using two main approaches including [16,17] the development of high-performance coating material and the development of uncoated fabrics. In the first approach, new coating substances such as silicone coating have been used to replace the traditional neoprene coating [16]. Silicone fabric coatings have been used for many years in many industrial fabrics such as conveyor belts, electrical and protective sleeving, and welding blankets. Silicone's high heat resistance and long-term aging stability make it appropriate for coating airbag fabrics [17]. It also results in lighter, thinner, and softer fabrics because of the smaller amounts needed in comparison with neoprene coating (almost twice the amount at the same level of heat protection). Another benefit of silicone coating is its compatibility with nylon fabric. Some experts suggest that neoprene coating generates hydrochloric acid during aging, which actively damages the fiber. The silicone coating provides a protective layer against hydrolysis and remains chemically inert. As it is well-known, uncoated nylon can be attacked by moisture (hydrolysis). Key performance characteristics of coating material for airbags include [16,17] good adhesion with the fabric surface, antiblocking, long-term flexibility, resistance to cyclic temperature changes (-40 to 250°F), ozone resistance, long-term stability, and low cost.

Developments toward uncoated airbag fabric were driven by the need for lighter and smaller thickness airbags that can easily fold and unfold. In addition, uncoated airbags can be easier recycled than coated airbags. To develop an uncoated airbag that can meet the desired performance discussed earlier, a great deal of effort in both yarn and fabric design must be made. In this regard, the key parameter is pore size and its distribution over the fabric area. Commercially, driver airbags are normally coated and are made from low-denier yarns. Passenger airbags may be uncoated, and they are larger in size as indicated earlier. This is justified on the basis that they impose lower gas pressure and have longer inflation time. These airbags can also be made from heavier denier yarns.

15.2.5 Design schemes of safety airbags

In view of the discussions earlier, one can imagine the magnitude of effort that must be made in developing an airbag fabric that can meet the different desired performance characteristics. Fig. 15.6 illustrates an example of a design scheme in which the different design parameters that can be controlled in an airbag fabric and the different performance characteristics related to these parameters. In a stepwise procedure,

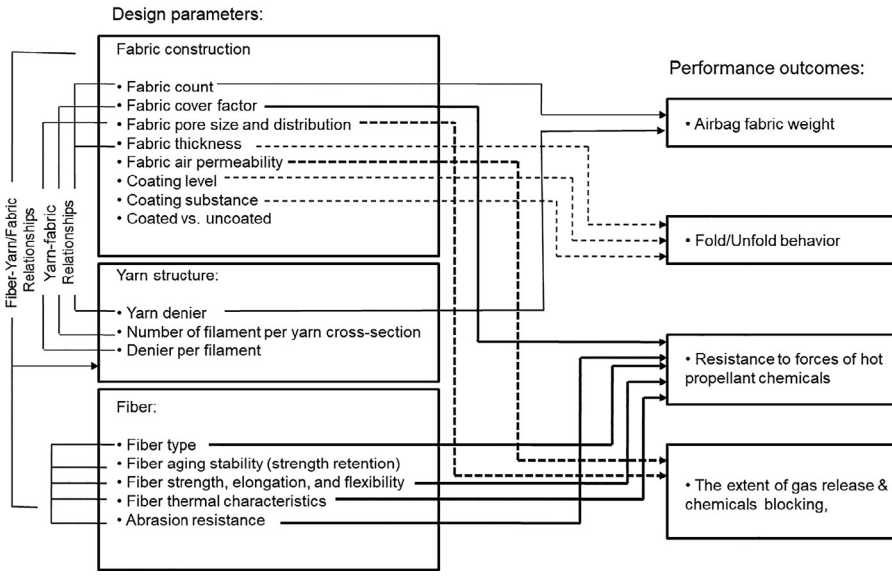


Fig. 15.6 Design parameters and related performance outcomes of airbag fabric.

appropriate fibers must be selected, suitable yarn deniers must be used, and fabrics of optimum construction and finish must be designed.

An optimum design of an airbag fabric will certainly require modeling analysis of its performance characteristics in relation to the various potential factors that may influence them. This analysis should yield analytical and simulative models that can ultimately be verified by extensive experimental analysis. Such models will be highly computation intensive as they should accommodate most of the parameters listed in Fig. 15.6 and different levels of these parameters. In addition, objective measures of performance outcomes, or response variables, should be established. These include the exact range of forces of the hot propellant chemicals used in the inflation, the threshold range of pores that will allow gas release and disallow penetration of chemicals, and the time required to unfold an airbag during deployment.

The issue of modeling airbag fabric performance was addressed in a study by Keshavaraj et al. [18]. In this study, the authors indicated that the material properties of engineering fabrics that are used to manufacture airbags cannot be modeled easily by the available nonlinear elastic-plastic shell elements used by the auto industry on the basis that a nonlinear membrane element that incorporates an elaborate tissue material model is highly computation intensive and does not differentiate between the various physical properties of the fabrics like fiber denier and weave pattern. Instead, the authors introduced a new modeling technique that uses artificial neural networks. Experimental permeability data for fabrics under biaxial strain conditions were obtained through a blister-inflation technique and were used to train the proposed network architecture. In this training environment, various properties of the fabric were incorporated, and the network was trained to generalize relative to the

environment. Typically, once a network is trained, a cause-and-effect pattern can be assimilated by the network with appropriate weights to produce a desired output. Fabrics tested in this study included nylon 66 fabrics with three different fabric deniers: 420, 630, and 840 and two types of weave and two 650-denier polyester fabrics having different calendering effects. The predictions obtained from this neural network model agreed well with the experimental data. This indicates that neural nets can be considered as a serious design tool in determining permeability and biaxial stress–strain relationships for textile fabrics used in airbags.

15.3 Developments of safety seatbelts

As indicated earlier, safety seatbelt is another important safety component that is used in all vehicles and aircrafts. Some historians trace back the origin of the seatbelt invention to the 1800s and its introduction in aircrafts to 1913. But recent history indicates that seatbelts first noticeably appeared in American automobiles in the early 1900s. A seatbelt is essentially an energy absorbing device that is designed to restrain an occupant momentum and movement during a crash, maintaining a safe distance between the occupant and harmful interior objects and reducing the load imposed on occupants during a crash down to survivable limits. Unlike the safety airbag, the seatbelt is locked in place by the occupant's choice, which requires a good awareness by the occupants of the safety merits of the seatbelt. In most countries, using seatbelts is enforced by law. Unfortunately, the use of seatbelts by all vehicle occupants is still a long way from becoming a reality. It appears that a combination of the restraining nature of seatbelts, the lack of awareness of its safety merits by some, and the tendency to oppose law enforcement associated with its use represents significant obstacles against its widespread use. From an engineering design viewpoint, these obstacles can be overcome through providing a combination of comfort and friendly restraining system. Today, new ideas are being introduced to further improve the performance of seatbelts. The common seatbelt used today is the so-called three-point belt, which is secured by two fittings on the floor and a third on the sidewall or pillar of the vehicle.

15.3.1 Performance characteristics and attributes of safety seatbelts

The key performance characteristics of a seatbelt primarily stems from its basic functions as shown in Fig. 15.7. Along the length of the seatbelt, high strength is a key requirement. An optimum combination of stretch and flexibility is also important in this direction, but they must be limited by the tightness effect that the seatbelt must impose in the case of a crash. In the width direction, flexibility is required to allow easy sliding through buckles. UV degradation resistance and aging stability also represent key performance characteristics of seatbelts.

Comfort is a key performance of seatbelts, which deserves more attention in the design process. This is due to the fact that a seatbelt not only imposes restrain on

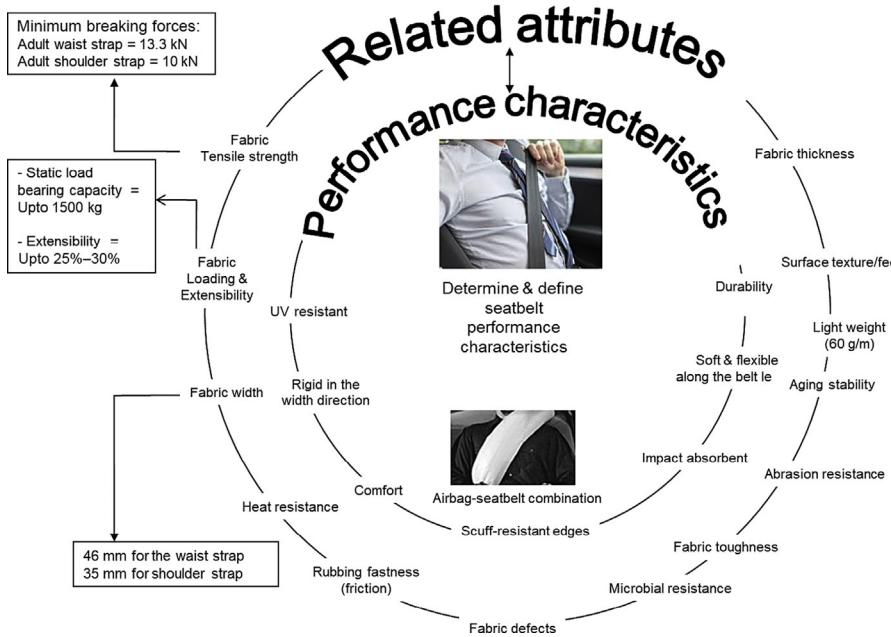


Fig. 15.7 Performance characteristics and attributes of safety seatbelts.

the occupant body during driving and in the event of a sudden brake or a crash but also imposes pressure on the waist, shoulders, and necks during driving, which can last for many hours and in various environmental conditions, particularly hot and humid climates. Complaints about the discomfort nature of seatbelts are often expressed by people of big body sizes. From a design viewpoint, comfort–safety relationships should be viewed in terms of the use-duration period. For example, an airbag is only felt for few moments, but other products may be associated with use-duration period of few minutes to few hours. In addition to seatbelts, other products associated with long uncomfortable duration periods include heavy bullet-proof vests, face masks used for contamination leak or medical operations, and fire-resistant uniforms worn during firefighting. The urgency associated with these products makes safety an overwhelming aspect in comparison with comfort. In the case of seatbelts, this urgency is not normally felt except for conscious awareness. Yet, seatbelts should are often required, as they should be, to be worn for different use-duration periods that can last for many hours.

The pressure against vehicle occupant's body imposes restrains against light body movement during traveling and is often associated with irritating rubbing against the body and around the neck–shoulder area. A great deal of this discomfort can be a result of poor adjustment of the seatbelt mount, and in many cases, it was found to be dependent on the extent of the geometric design of seat belts matching the occupant's anatomical characteristics (e.g., shoulder belt fit, seat belt upper anchorage location, and seatback angle). However, the constant contact between the seatbelt and the human

body represents a significant source of irritation. This aspect provides an opportunity for fabric design engineers to develop narrow fabrics that can generate a pleasant (cushioning) feel against human body with minimum contact pressure. Generating ideas in this direction face a fundamental design trade-off, which is the need for wider (more contact area) seatbelts to distribute the pressure against human body, or ultimately the impact force during a crash, over a larger area of the body versus smaller seatbelts that exhibit minimum contact with the body. This is an area that requires more research investigation as this may lead to the best design compromise. This point could also be a sparking application of smart textiles to develop smart seatbelts that provide comfort to big-size users particularly when high pressure is exerted.

15.3.2 Fiber selection for safety seatbelts

Many fiber types have been used for making seatbelts, but the most commonly used fibers are polyester and nylon fibers. Polyester fibers are commonly preferred to nylon fibers based on their relatively lower extensibility. For example, Securus fiber was developed specially for safety seatbelts [19,20]. This is a new category of polyester copolymer fibers developed for managed-load applications. It combines polyethylene terephthalate (PET), for restraining properties, and polycaprolactone (PCL), for flexibility and cushioning. It is claimed to yield optimum energy absorption. According to the developer, "Securus fibers deliver a three-step reaction in an accident: "first, the high-strength fibers hold passengers tightly in place at impact; then, Securus fibers relax or stretch as needed to limit the force on the occupant and cushion the body's movement into the airbag; finally, the fibers hold again as the car halts and prevents the passenger from hitting the steering wheel, dashboard, or windshield as the airbag deflates'. In response to different seatbelts performance requirements, wide ranges of physical attributes of Securus fiber can be tailored as shown in Table 15.4.

Table 15.4 Different value levels of different physical attributes of Securus seatbelt fiber [16].

Parameter	Level I	Level II	Level III	Level IV
Denier	500	1000	1350	1500
Decitex	550	1100	1500	1670
Filament count	35	70	100	100
Breaking strength (Kg/N)	2.8/27	7.0/68.6	9.5/92.7	10.5/102.8
Tenacity (g/d)/(cN/dtex)	5.5/4.9	7.0/6.2	7.0/6.2	7.0/6.2
Elongation at break (%)	27	27	27	27
Toughness (g/d)/(cN/tex)	0.9/0.8	0.9/0.8	0.9/0.8	0.9/0.8
Thermal shrinkage at 177°C (%)	16	20	16	16

15.3.3 Seatbelt yarns and fabrics

Fabrics used for seatbelts are typically twill-woven narrow fabrics (46 mm for the waist strap and 35 mm for shoulder strap for adults) made from continuous polyester filament yarns [20]. Common fabric constructions include [21,22] 320 ends of 1100 dtex yarns and 260 ends of 1670 dtex yarns. In the filling direction, typical yarns are of 550 dtex. Seatbelts made from nylon filaments are typically woven from 180 dtex yarns in the warp direction and 470 or 940 dtex yarns in the filling direction. These constructions are chosen because they allow maximum yarn packing within a given area for maximum strength and good abrasion resistance.

Commercial needle looms used to weave seatbelt fabrics can accommodate six weaving stations simultaneously side by side. The weft is inserted at right angles to the warp direction from one side of the loom and a selvedge is formed. The other side of webbing is held by an auxiliary needle, which manipulates a binder and a lock thread. Once these are combined with the weft yarn, a run-proof selvedge is created. Special care is taken when constructing the selvedge to ensure high integrity. Woven seatbelts are typically transferred under tension to a dyeing and finishing range where the gray webbing is dyed and heat set [20,21]. The purpose of heat setting is to control the extent of extensibility in the seatbelt. Linear fabric weight in the gray state is about 50 g/m, and upon finishing, it is increased to about 60 g/m as a result of the shrinkage in the length direction induced by heat setting to improve the energy absorption properties. Seatbelts may also be lightly coated to improve cleanability, durability, and ease of passage in and out of housing and to impart some antistatic properties.

15.3.4 Development of integrated seatbelt-airbag (inflatable seatbelt) systems

As indicated earlier, airbags and seatbelts represent two essential safety components in a vehicle that if activated simultaneously at the time of crash can certainly save lives and reduce serious injuries associated with car crashes. In recent years, many efforts have been made to develop integrated seatbelt-airbag systems [20–22]. The common term used to describe an integrated seatbelt-airbag system is inflatable seatbelt. Basically, an airbag-seatbelt system is a tubular seatbelt that can inflate at the time of the crash to provide a protective cushioning effect to the occupant. In some developments, the seatbelt is held by weak stitches that burst open when the seatbelt is inflated. Under impact, the surface seatbelt increases by over 400% in surface area than the normal flat seatbelt. These seatbelts are designed to be fitted in the rear seats of the vehicles, and they can replace conventional airbags in this area.

One of the examples of inflatable seatbelts is the model introduced by Ford Motor Company, which consists of a tubular inflatable bag inside the shoulder belt that inflates upon a vehicle crash, protecting the passenger's head and neck by limiting forward motion. Another example is the AAIR aviation inflatable restraint developed by AM-SAFE for use in aircrafts. This system comprises a standard lap belt modified with an inflatable bag that is connected to a cold gas generator and an electronic sensor

activation box. The entire unit is self-contained for each seat. The sensor determines when to activate the airbag to provide the required protection.

15.4 Developments of transportation seats

A seat represents the most intimate part in a car or an airplane. The apparent function of a seat is to keep passengers in place during the duration of a trip. However, many cars are totally rejected by consumers solely based on the style and the design of car seat; this is called "ergonomic-design failure." A car seat is very different from a desk seat. A driver using the steering wheel must have his/her hands and arms higher than that encountered in a desk seat. To operate the brake and accelerator pedals, the driver must be able to extend legs more forward; one foot may be flat on the floor and the other at an angle to operate the accelerator and brake pedals. In cars using a standard (manual) transmission, the driver's foot is on the clutch with one arm and hand operating the gear shift. The continuous car vibration during driving specially on bumpy road surfaces requires a design of car seats that can absorb energy, resist forces against human body, and yield smooth and comfortable seating. Complaints associated with improperly designed car seats include lower back pain, foot cramps, stiff neck, and sore shoulders from poor posture, stress, tension, and staying in one posture or position for an extended period.

When we switch to airplane seats, we will find them to be a significant source of discomfort to most travelers, particularly in economy class. Airplane seats are typically designed using the "one-size-fits-all" concept, and it is only a matter of time before this traditional design concept turns against the airline industry through legal disputes that will ultimately lead to innovative designs. Reserving a seat on an airplane only requires the name of the traveler and his passport's number. A traveler being a large size, obese, very tall, or very short is irrelevant in airplane accommodation, and it is being dealt with on case-by-case basis. Indeed, most of us traveling on an airplane will often have one concern in mind, which is where to be seated and the size of the traveler sitting next to us. Some readers may remember the story of the actor-director Kevin Smith, who often used two seats to be able to fit his big body. The actor was once asked to leave a Southwest Airlines flight because of his body size. When some airlines announced that it would enforce a policy requiring some larger individuals to purchase an additional seat, they were widely criticized.

From a design' perspective, an airplane seat is subject to noticeable dynamic forces during the takeoff and the landing of an airplane. During normal flying, these effects are minimized due to dynamic balance. These aspects are considered in the design of airplane seats. Furthermore, different seat designs and layout configurations are developed to recognize and accommodate passenger anthropometric variations (differences in body sizes). The problem, however, stems from the fact that these design options are constrained by the space allowed in airplane or, more precisely, the number of seats in the airplane space; fewer available seats can significantly impact the airline's current pricing models. This situation represents a classic case of conflict between economic factors and ergonomic-design factors with the sole victim being the traveler.

This means that a key question in the design conceptualization process must be whether a traveler would be willing to pay more money for more comfort. Most airlines assumed that the answer to this question is "no" as evident by the substantial difference between seats in the first class, occupied by few travelers, and those of the economy class (most travelers).

15.4.1 Automotive seat members

For automotive seats, there are two categories of components: structural frame members and nonstructural components. A structural frame member is usually made of steel that has been formed into tabular configuration or of stamped or rolled sheet metal. This provides the weight support of both the seat and the occupant and forms the shape and the cushioning aspects of the seat. From a design viewpoint, the trade-off here is "safety and strength versus energy saving." In this regard, the anchoring frame strength typically requires heavy weight and stabilized anchoring geometry, while energy saving typically requires a low frame weight. The frame member commonly consists of a seat base and a backrest component. Commonly, seat bases are made of a shallow steel trough, roughly 1 mm thick. Some seat frames being developed are designed using aluminum seat base and a backrest structure made of rolled high-tensile steel sections. A steel construction is stronger than aluminum or magnesium, which is important for providing better energy absorption in the event of a crash. However, weight being a consideration for energy saving makes a combination of steel and aluminum an appropriate way to achieve a considerably lower weight for the backrest (roughly 25% less), since light-alloy structures need a much greater wall thickness for the same strength. These developments aim at a target weight of automotive front seats ranging from 11 to 18 kg. Composite structures have also been highly considered for the design of seats.

Nonstructural seat components include cushions, springs, and upholstery that provide optimum contact, appropriate load distribution between the occupant and the seat frame, and comfort features via optimum contour and seating geometry. Our focus will be on seat fabric component. In this regard, three basic components associated with any seat should be considered: (1) seat cover laminate (face fabric, foam, and scrim), (2) seat back (squab), and (3) seat bottom (cushion).

Under normal steady-state rides, the seat should support or anchorage transmit compression, tension, and shear forces from the seat to the floor or side structure. In the event of collision or sudden brakes, the resulting forces are transmitted in reverse direction from floor to seat. As a result, the seat anchorage structures and attachments require a design of adequate strength to accommodate seat and occupant inertial forces. A seat cover can be considered a triple-laminate system [23–25]. The fabric is normally laminated to polyurethane foam (typically, 2–10 mm thickness) to keep it in an uncreased state. This lamination process allows easy cleaning of seat covers and imparts a soft touch to the fabric. In addition, it allows deep attractive sew lines in the seat cover. It helps the seat cover slide along the sewing machine surface during sewing and assist sliding when the made-up cover is pulled over the seat structure; a scrim fabric is also laminated to the other side of the polyurethane foam.

This helps control the stretch properties of the seat cover especially when knitted fabrics are used. The polyurethane foam to which the cover fabric is laminated can be of two general types, polyester polyurethane foam and polyether polyurethane foam. Both types can be made into different flame-retardant (FR) grades. Polyether polyurethane foam needs to be modified slightly with certain additives to make it flame retardant.

Different methods utilized to fabricate automotive seat covers were reported in Fung and Hardcastle book [6]. The traditional method to fabricate a seat cover system involves cutting and sewing of panels of the seat cover laminate (face fabric/foam/scrim) into a cover, which is then pulled over the squab (seat back) and cushion (seat bottom) and then fixed in place using a variety of clips and fastenings. In addition to the traditional method, many other methods are implemented by different companies. These are summarized later:

- Foam-in-place technique [23,24]: This method combines the processes of foam cushioning and squab molding with the fixing of the seat cover in place over the premolded foam. Panels of the seat cover laminate are cut and sewn into a "bag," and the liquid foam components are poured in to form the solid foam through internal reaction. Polyurethane barrier is also included to prevent the liquids seeping through the fabric cover laminate before the reaction is complete.
- Direct joining method [23,24]: This technique is based on joining the cover fabric laminate directly to the squab and cushion. It results in a smaller thickness of the laminate foam, which assists in fabricating seats of curvaceous and rounded contours. Direct joining is achieved using either hot-melt adhesive films or solvent spray adhesives. The basic flaw with this method is that it can adversely affect the pile in velvet fabrics.
- Hook-and-loop fastenings [25–28]: This method is based on using hook-and-loop fastening components (e.g., Velcro products) made from raised, knitted nylon 66 (or polyester) fabrics. The hook part of the fastener is attached to the seat foam cushion and the loop part sewn to the cover. When brought together, a very strong join is produced.
- 3-D knitting of car seat covers [27–29]: This method is based on knitting fabric in one piece to avoid panel cutting and sewing and reduce material waste. The entire operation is computer controlled to form a predesigned single 3-D shaped piece.

15.4.2 Performance characteristics of transportation seats

The key performance characteristics of transportation seats are durability, comfort, and safety (see Fig. 15.8). These characteristics are discussed in some detail in the following sections. An optimum balance between these characteristics represents a true design challenge, particularly in view of the critical need for sufficiently light weight to achieve fuel economy and minimize inertial stresses encountered during a crash.

15.4.2.1 Durability aspects of transportation seats

Although transportation seats are expected to survive over the entire service life of the vehicle or the aircraft, they may fail or deteriorate under many circumstances and because of many factors including excessive external stresses, harsh environmental

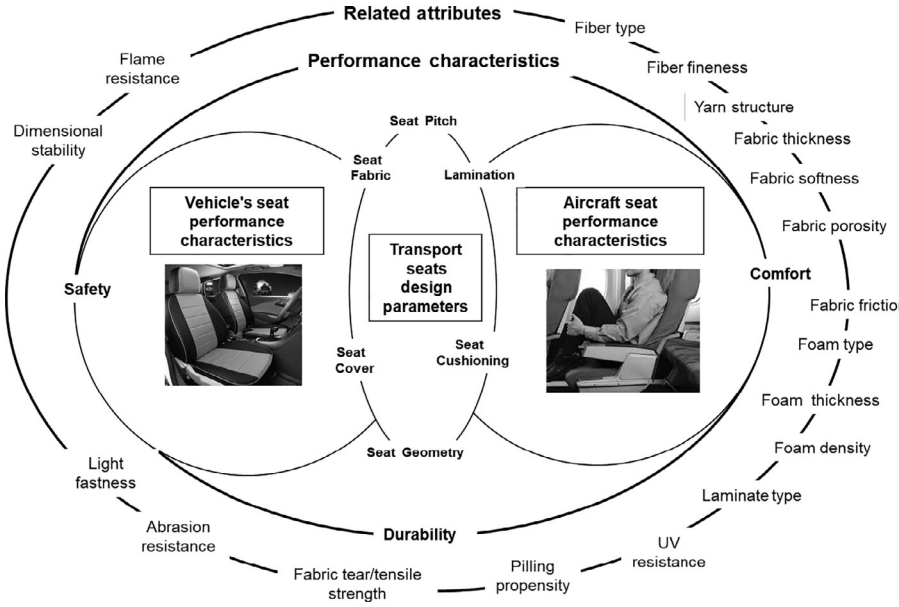


Fig. 15.8 Performance characteristics and attributes of transportation seats.

factors, flame or high heat, and stain or dirt. The most noticeable potential cause of seat failure is the loading of the seat by the occupant's body mass, particularly in rearward direction. Seat failure is also expected in the event of a crash due to the relative acceleration of the occupant's body mass during a collision. More serious than the failure of the transportation seat is the impact of this failure on the occupants. For example, it is commonly known that when an automobile front seat fails in a rear-end collision causing the seat back to move suddenly rearward, serious hazardous conditions can be encountered including [30,31] the loss of control (exposing occupants to multiple crashes), seat ejection, and interior impacts. These aspects can be handled in the design phase of transportation seats using stress-strain analysis of all potential forces applied on the seat under both static and dynamic conditions. One of the key factors that should be considered in failure analysis is the variability aspect resulting from variation of occupant size and weight and the variable scenarios of a vehicle or aircraft crash. This aspect should be handled through probabilistic design in which these variables are simulated by some forms of probability distributions [32].

In the context of seat cover performance, key attributes related to mechanical durability include fabric tear strength, fabric tensile strength, abrasion resistance, and pilling propensity. Different levels of these attributes can be selected and controlled through appropriate selection of fiber type, yarn structure, fabric construction, and fabric finish. These attributes have been a part of the basic specifications of upholstery fabrics used for transportation interiors for many years.

Most transportation units are likely to be subjected to harsh environmental conditions during their service life. The need for lighter vehicles has resulted in new styles

and body shapes that led to more exposure of vehicles interiors to the surrounding environment. Examples of these styles include slanting glass and larger windows, which in turn led to more exposure to sunlight. Through glass, which is transparent to visible light, vehicles interiors can be heated to temperatures well above 100°C. Vehicle interior can also be exposed to levels of relative humidity ranging from 0% to 100%. Severe heat and humidity conditions can result in substantial degradation of seat covers reflected in color fading and surface deterioration that can in turn influence the mechanical resistance of vehicle seats. In the design analysis, the key factors in dealing with the environmental effects are fiber type, yarn structure, fabric construction, and finish treatment.

Flame resistance represents a durability and safety factor not only for transportation seats but also for the entire interiors from carpets to sidewalls and roof interiors. As a result, most design analysis involves a great deal of emphasis on this aspect. There are many ways to minimize the impact of flame by containing its propagation that can be implemented in the design of transportation units. Similarly, stain effects are handled through the design of fibrous structures that are stain repellent and the use of stain-resistant finish.

15.4.2.2 Comfort aspects of transportation seats

In recent years, consumer demands for comfort have increased as a result of the increasing tendency to reduce the size of transportation units, or the space allocated per occupant (e.g., in aircrafts), and the exponential increase in aircraft passenger population. Under normal traveling conditions, restraining an occupant in a single location in the vehicle is a mild source of discomfort, although many children would consider it a severe restrain. As travel duration increases, the extent of discomfort will likely to increase resulting in driver's fatigue that could contribute to safety hazards. For some professions (e.g., truck drivers, salesmen, and postage or package carriers), 50 or more hours a week of driving represents a common duration. This amounts to over 2300 h of driving per year. In aircraft travel, long hours of flying associated with seating restrictions, sometimes under severe conditions of air turbulence, is an experience that most of us are familiar with. Most airlines would like to reduce seat pitch and seat width to fit more seats per aircraft for obvious economical reasons. On the other hand, people are getting bigger in size, and obesity is becoming a global epidemic. Various sources of statistics on overweight and obesity suggest a significant climb in world overweight population. Some estimates indicate that 30% of the world today is overweight. In the United States alone, over 60 million people are overweight, 40 million obese, and 3 million morbidly obese.

Automotive and aircraft seating comfort has been discussed in many investigations in which two main human-related aspects were commonly addressed [33–39]: anthropometry and ergonomics. Anthropometry is the study of human body measurements to design ergonomic furniture in view of body variability. Ergonomics deal with the design for maximum comfort, efficiency, safety, and ease of use, both in the workplace or in areas in which long stay duration is expected. As a result, both vehicles and aircraft seats should be developed in an iterative way based on subjective

feedbacks from occupants to support the analysis. Obviously, the time and cost associated with the iteration analysis could be justified if the process was guaranteed to produce comfortable seats. Unfortunately, most design analyses of transportation seats tend to overlook this matter, relying totally on objective and measurable laboratory standards.

To incorporate comfort-related features in the design of automotive and aircraft seats, it will be important to understand the specific potential causes of discomfort associated with them. These can be divided into two main categories: physical causes and thermal causes. The first category deals with human body interaction with the seat, and the second deals with heat and moisture flow between the body and the seat cover.

Physical comfort of transportation seats

A transportation seat should provide support to the occupant body to remain in place and a pleasant physical interaction with sensitive parts of the body such as the back, neck, and waist. Accordingly, key physical aspects of seating comfort include seat/body interface pressure distribution, pressure change rate, and body vibration. These are anthropometry-related aspects that have been studied extensively by many researchers. Design engineers should refer to the numerous findings in this area as part of their information gathering phase. For example, the characteristics of pressure distribution on a rigid seat under whole-body vehicular vibrations were thoroughly studied by many researchers [37–39]. Some of these studies [37] developed ways to measure and predict the seat pressure in the context of driver's discomfort for the purpose of providing engineers and manufacturers with key design information. Techniques for measuring seat pressure distribution and area pressure change were also proposed for truck seating in the context of evaluating the cushioning effect of transportation seats on driver's comfort [40].

One of the benefits of evaluating the physical comfort of transportation seats is the introduction of alternative cushioning systems that can apply gentler and more acceptable pressure against human body. For example, air-inflated (or pneumatic) seats were found to provide significant improvement in pressure distribution in the seat cushion–occupant interface than the traditional foam cushion [40–42]. Most studies revealed substantial differences between the dynamics of foam cushions and those of air-inflated cushions, particularly in terms of their interface with the human body. Other advantages of using pneumatic seats over foam seats included reduced weight, avoidance of using flammable substances, the possibility of more variable adjustment options of seat height, inclination, shape, and surface hardness. Pneumatic cushions also open the possibility for additional options such as body massaging and temperature control in the seating system.

Body vibration represents another cause of physical discomfort, particularly vertical vibration caused by road irregularity or severe air turbulence in the case of airplanes. A significant portion of this vibration is transmitted to the body (buttocks and back of the occupant) through the seating system. Typically, the natural frequency for the human trunk falls in the range of 4–8 Hz. This is commonly the frequency range

within which the whole body is expected to vibrate [42,43]. From a design viewpoint, seat geometry is the key parameter in dealing with the mechanical energy absorption characteristics of seated occupants under vertical vibration. Some studies suggested that the absorbed power quantity increases in a quadratic manner with the exposure level by the person and that the absorbed power is strongly dependent upon the individual anthropometry variables such as body mass, fat, and mass index [44].

When the focus is on the physical comfort provided by the seat cover system, key design attributes will include fiber type, yarn structure, fabric thickness, fabric surface texture, fabric frictional characteristics, foam type, foam thickness, and foam density. These parameters should be incorporated in the design analysis, particularly in the simulation and modeling phase. In this regard, design engineers of seat cover systems should be referred to some of the models developed for simulating the dynamics of seating systems [45–52].

In addition to the earlier factors, it is also important to consider the fitting aspects of seats. In this regard, seat design parameters can be divided into three categories [45–48]:

1. Fit-parameter levels, determined by the anthropometry of the occupant population and that include such measures as the length of the seat cushion.
2. Feel parameters that relate to the physical contact between the sitter and the seat and include the pressure distribution and upholstery properties.
3. Support parameters that can affect the posture of the occupant and include seat contours and adjustments.

Thermal comfort of transportation seats

Analysis of the thermal comfort provided by a transportation seat is a very complex one, primarily due to the multiplicity of interface media in a vehicle or an aircraft. These media include body–garment interface, garment–seat interface, and seat–surrounding interface. Analysis of these interfaces is further complicated by the dynamic media change during traveling. This means that an occupant may suffer from multiple heat or cold sources simultaneously in a vehicle or an aircraft. To deal with the problem of thermal comfort of a transportation seat in design analysis, it is important that engineers understand the basic concepts of thermophysiological comfort. Concepts discussed in Chapter 5 will largely hold for the situation of transportation seating. However, interpretation of these concepts should be modified in view of the dynamic and transient nature of the thermal environment in a vehicle or an aircraft. A comprehensive modeling analysis of seating thermal comfort should account for many factors including (1) a double fabric layer system consisting of the garment worn by the occupant and that of the seat cover; (2) the squab and cushion underneath the seat cover, or the role of foam material and foam thickness as additional barriers to the escape of perspiration; and (3) the role of foam material as a heat insulator. From a design viewpoint, critical factors that should be considered in relation to thermal comfort include [53,54] fiber type, fiber fineness (e.g., normal or microdenier), fabric structure (e.g., flat, velvet, and jacquard), and laminate type.

Despite the significant developments made in recent years, thermal comfort still represents a design challenge in both vehicle and aircraft seating systems. Seats of modern vehicles are still hot and sticky in hot and humid environment, and they provide low insulation in cold environment. This challenge has led to the consideration of alternative components such as "bead" seats to provide cooler sensation in hot environment as a result of the air gaps they create between the skin and the seat, thus allowing some air circulation and sweat evaporation. However, these alternatives do not provide optimum tactile comfort in comparison with fabric material.

Safety aspects of transportation seats

A seating system in a vehicle can provide safety features that are as important as those provided by safety air bags or seat belts. In frontal and rear-end crashes, the seat frame and seat back contain the occupant and keep him/her in an upright position, and the seat cushioning absorbs some of the energy generated by the impact. The key issue here is for the seat not to collapse in the event of a crash. From a design viewpoint, the safety criteria of a seat should be addressed in conjunction with both the air bag and the seat belt mechanisms discussed earlier. It should also be addressed in relation to the other seat criteria, namely, durability and comfort. For example, the trend of replacing traditional foam material with pneumatic seat systems has been mainly based on meeting comfort and lightweight specifications, particularly under normal traveling conditions. When safety is considered, particularly in the event of a crash, the question becomes whether pneumatic seats are crash-worthy components or not.

15.4.3 Fibers used in transportation seats

The selection of fiber type for transportation seat fabrics has evolved over the years with the development of new fibers. Initially, seats were made from natural fibers such as wool and cotton. These fibers suffer low abrasion resistance, and they were highly moisture absorbent. Later, synthetic fibers, from rayon to polyester, dominated this market because of their superior durability and moisture absorption features. Today, the most commonly used fiber for seat fabric is polyester. This is primarily because of its high strength, high abrasion resistance, relatively high UV degradation resistance, good mildew resistance, and good resilience and crease resistance. The main problem associated with polyester fabric is its low moisture absorption. This problem is overcome by using hydrophilic surface finish or by blending polyester with other fibers such as wool fibers. Polyester fabric is typically treated with special finish to improve its UV resistance. In addition to common rounded polyester fibers, multichannel polyester fibers are also evaluated for the design of transportation seats because of their good moisture transfer, easy dyeability, and stain protection [54]. Acrylic fibers are also used at smaller quantities in some vehicles. This fiber has superior UV degradation resistance but suffers poor abrasion resistance in comparison with polyester fiber. Polypropylene fibers have been also tried because of their light weight and easy recyclability. However, problems such as dyeability and low abrasion resistance have hindered this fiber type from being widely used in transportation seat material.

In recent years, some developments have been made to use polyester and wool fibers including recycled fibers in a nonwoven assembly as a replacement to polyurethane laminate foam [55,56]. Another development toward replacing foam material by fibrous material was the use of spacer knit fabrics, which is a fabric construction in which yarns are raised perpendicular to the fabric plane and sandwiched by two knit layers. Design challenges associated with using fibrous assemblies instead of laminate foam material include significant loss in thickness under compression and the difficulty to duplicate the pure isotropic structure of foam, as fibrous structures often exhibit partial anisotropy.

In addition to the earlier design problems associated with the use of fibrous materials in replacement of other parts of the seat, resilience at high temperatures and geometrical integrity in comparison with polyurethane foam also represent difficult matters. One attempt to overcome these problems was by using polyester fiber clusters of coiled and fluff configuration, introduced by DuPont. The clusters are put into a mold made of perforated metal, and hot air is applied, which bonds the clusters together. Claims by DuPont regarding this development include [2,57] the following:

- Weight savings of up to 30%–40% resulting from using polyester clusters instead of foam
- Equivalent seating support to that of foam associated with easier disassembly and recycling
- Better comfort through increased breathability

Another development made by Toyobo is the so-called BREATH AIR, which consisted of random continuous loops of a thermoplastic elastomer. This development was also associated with similar claims of comfort and recyclability [58]. In addition, some natural fibers such as jute, sisal, and kapok are also being considered for use in seats as alternatives to polyurethane foam [2].

Developments to replace urethane foam in seat cushions with fibrous materials were also extended to aircraft seats. In this regard, the objectives were to achieve superior flame resistance, light weight, and durability. One of these efforts was based on using pitch-based carbon fiber manufactured by Osaka Gas as a substitute to urethane foam. This fibrous material was highly incombustible, produced no harmful gas, and exhibited light weight.

15.4.4 Yarns and fabrics used in transportation seats

To meet the performance characteristics of transportation seats, both yarn structure and fabric construction should be optimized with respect to key attributes such as tensile strength, abrasion resistance, pilling propensity, porosity, moisture absorption, and resilience. From a design viewpoint, optimum levels of these attributes should be selected in such a way that can create a good balance between the key performance characteristics of seat fabrics, namely, durability, comfort, and safety. In this regard, yarns can be made of different structures from spun to continuous filaments and of a wide range of counts and twist levels. However, spun or twisted yarns typically suffer poor abrasion resistance.

In practice, air-textured yarns dominate the market of transportation seats. The main reason for this domination is the common agreement among most seat

designers that air-textured polyester yarns meet the balance of durability and comfort. Air-textured polyester yarns are made from a wide range of deniers depending on pre-specifications associated with lamination and foam materials used. Many yarns can be doubled during air texturing to create core/effect structures. Yarns are typically dyed in the yarn form. This means that precision winding of yarns and minimum yarn defects are key requirements.

Seat cover fabrics can be made from different fabric constructions including [2] flat woven fabric of 200–400 g/m^2, flat woven velvet of 350–450 g/m^2, warp-knit tricot with pile surface of 280–380 g/m^2, and circular knit fabric with pile surface of 160–230 g/m^2. For flat woven fabrics, partially oriented yarns (POY) are typically used. Typical basic yarns used for woven fabrics are 167 dtex, 48 filaments. These yarns are typically quadrupled to form heavier yarns of 668 dtex, 192 filaments, and 835 dtex, 240 filaments made from five ends of basic yarns. For knit fabrics, lighter yarns of about 300 dtex are used.

As indicated in Chapter 10, woven fabrics typically have higher strength and higher abrasion resistance than knit fabrics. However, they exhibit lower stretch, which makes them less flexible in seat cover laminate fabrication. From a design viewpoint, consideration of some elastomeric materials may be an option for enhancing the stretch of woven fabrics. Another option is to use another fiber type of higher stretch than the traditional polyester fibers that share the same positive features such as polybutylterephthalate, PBT. This type of fiber is significantly more expensive than regular polyester [2]. The most expensive fabric used in seat covers is flat woven velvet fabrics. In addition to stretch, knitted fabrics with raised surfaces provide desirable softness to the touch than flat woven fabrics.

15.4.5 Finish applications in transportation seats

As indicated earlier, yarns used in seat cover fabrics are typically package dyed. This omits the need for dyeing in the fabric form. However, different forms of finishing must be applied in the fabric form to meet the desired performance characteristics [2]. In this regard, woven fabrics may be scoured, stentered, finished, and laminated before cutting and sewing. Warp knit fabrics are typically brushed, stentered, scoured, finished, and laminated. Weft knit fabrics on the other hand are typically sheared, scoured, stentered, finished, and laminated. Three-dimensional knits are typically heat set before fitting to provide structural stabilization. Note that stentering is an essential finishing phase of all seat cover fabrics. This is because stentering provides a stable, flat, tension-free substrate for lamination and eventual seat fabrication [2]. It is also important that any finish used should be applied in such a way that will not hinder the adhesion capability during lamination. This is one of the reasons why silicon-based finishes are often avoided in seat cover fabrics.

Seat cover fabric can also be coated either to improve some performance characteristics or to maintain the integrity of fabric structure. For example, some woven fabrics may be coated with acrylic or polyurethane resin to improve flame resistance and abrasion resistance. On the other hand, woven velvets are coated to improve pile

pull-out properties. Finally, the continuous need for styles and appearance changes in modern cars has led to more attention to the printing aspect of seat cover fabrics.

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Performance characteristics of technical textiles: Part III: Healthcare and protective textiles

16

16.1 Introduction

In this chapter, the focus is shifted to fibrous materials used as an integral element in healthcare products and protection applications. Healthcare products are generally described as "medical textiles." These products may range from simple gauze or bandage materials to scaffolds for tissue culturing and a large variety of prostheses for permanent body implants. Protective textiles cover a wide range of products including textiles used in extreme climates, fibrous products used for ballistic protection, and flame-resistant textiles. These two categories of products are associated with growing markets that are already in the order of billions of dollars, and they are inevitably to grow in years to come.

The exponential growth of the use of fibrous and polymeric materials in the medical field has led to the creation of an independent industry category called "medical textiles." Estimates from data provided by the US International Trade Administration (ITA, https://www.trade.gov/) indicate that the global medical device market will approach over $400 billion by 2020, with over 6% of this market in medical textiles. About 30% of medical textiles will be used in critical applications such as implantable devices (e.g., surgical sutures, hernia meshes, vascular and endovascular prostheses, artificial skin, and anterior cruciate ligament). As one can imagine, the growth of this market is potentially unlimited by virtue of the revenues and profits it can create due to the value-added aspect of its products. However, it is also a substantial liability market facing very strong regulatory challenges. As a result, many key factors will always represent critical aspects in this industry that can drive the cost much higher than that anticipated in traditional textiles. These factors include (a) the capacity to deliver safe and reliable innovations, (b) the need for well-established R&D, (c) the need to hire top-qualified working personnel from various backgrounds, (d) the need to create new technologies that meet performance and safety standards, and (e) the time-to-market pressure.

In contrast with medical textiles in which consumers represent people of all ages and in different regions around the globe, protective textiles are growing more in industrial countries where human safety and protection regulations are well established by governments and industries. Protective textiles are used in numerous applications including worker safety, protection from fire, protection from toxic and chemical agents, military and law-enforcement protection, and protection in construction sites. These applications trigger the demand for specialty protective clothing that can minimize injuries, maintain safer working environment, and save lives.

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The global protective textile market is also growing at a steady rate. In 2018, this market was valued at over $7.0 billion, but it is likely to grow at a higher pace as many more regions around the world establish their own safety standards in the workplace and in high-risk applications.

16.2 Medical textiles

The development of healthcare textiles is typically associated with multiple requirements that are often reflected in true challenges facing the design of safe products with optimum performance characteristics. These include the following:

1. Understanding the specific purpose of using a medical product
2. Understanding the functional characteristics of the product
3. Understanding the assembly aspects of a product including material fitting, manipulation ease, compatibility, interactivity, causes of potential failure, expected lifetime, and dimensional stability
4. Understanding the interactive nature between fibrous or polymeric materials and body organs and fluids
5. Understanding all possible side effects resulting from using certain materials including toxicity, allergic effects, expansion or contraction effects, and failure to accommodate cell growth
6. Understanding of the latest technologies for polymer synthesis, fiber spinning, surface modification, and nanotechnology
7. Understanding basic and advanced concepts of biological science
8. Understanding the liability nature of medical textiles and all regulatory aspects
9. Understanding the effects of disposable medical products on the environment and the cost associated with handling these wastes
10. Understanding the cost aspects of design including performance/cost ratio and safety/cost ratio

The aforementioned requirements certainly call for a multidisciplinary approach to the design of healthcare textiles in which joint effort must be made between polymer scientists, physicists, biologists, chemists, pharmacists, druggists, physiologists, engineers, etc. As one can imagine, these are extremely different fields that have minimum or no common educational background, and they use different technical vocabularies. Therefore, the true challenge is not merely in getting these backgrounds around one table in a design project but to coordinate and integrate their thoughts and efforts for the purpose of developing a healthcare product. This task must be led by a top product developer with a great deal of knowledge in different technical and application aspects.

Medical textiles represent a unique field from both marketing and product development perspectives. The market is certainly very large, highly diverse, and rather complex. It consists of products that are produced in masses, generating billions of dollars in revenues and profits, such as diapers and wipes that are sold over the counter in millions of retail and grocery stores around the world. It also consists of numerous utility healthcare products such as bandages, wound dressings, wraps and plasters for

making casts, medical tapes, gauze, wadding and absorbent pads, compression, barrier, hygiene products, surgical gowns, gloves, masks, aprons, and other hospital products that are sold in millions of pharmacies and medical supply stores around the world and generating billions of dollars in revenues.

Another category of medical textiles is the high-specialty products used mostly for medical applications inside the human body. These products are not as massive as the other products, and they are subject to very strict regulations and extensive qualification criteria associated with each product. Examples of these applications include the following:

- Implantable applications such as sutures, heart valves, hernia mesh, artificial ligaments, vascular grafts, and artificial joints. These are products intended to assist in restoring body functions, improve the quality of life, and certainly save lives. Some implantable medical devices are implanted long term and contain electronic circuits and batteries.
- Extracorporeal devices are mechanical organs used in blood purification such as apheresis, hemodialysis, hemofiltration, plasmapheresis, or extracorporeal membrane oxygenation. Textiles are used in these devices essentially as filtration media to support the function of vital organs (e.g., artificial kidney liver devices and mechanical lungs). These devices must possess certain requirements including antiallergenic, anticarcinogenic, resistance to microorganisms, antibacterial, nontoxic, and the ability to be sterilized. The function and performance of these devices depend on the adsorbent used.
- Prosthetic devices designed to replace missing body parts while providing acceptable levels of functionality. Many of the newer prosthetic devices incorporate composite elements to reduce weight, improve fit, and enhance functionality. Newer advanced textile systems also are being used to improve the interface between the device and human tissue and nerve systems.
- Orthotic items used as corrective devices such as insoles and braces to improve functional characteristics of the neuromuscular or skeletal systems.

16.2.1 Fiber types used for healthcare products

The need for fibrous materials in medical applications stems from a number of unique attributes including light weight; flexibility; softness; manipulability; biocompatibility; biodegradability; good resistance to alkalis, acids, and microorganisms; good dimensional stability; elasticity; zero contamination or impurities; absorption or repellency; air permeability; and nontoxicity. These attributes are essentially determined by fiber type and other additives that contribute significantly to the key functional performance characteristics of healthcare products [1–4]. Fig. 16.1 illustrates examples of fiber types used in the medical field categorized in two different ways: by source (natural, synthetic, and specialty fibers) and by body reaction or absorption (biodegradable and nonbiodegradable). In most applications, fibers should originate from polymeric structures that are linear, long, and flexible; their side groups should be simple, small, or polar; and their chains should be capable of being oriented and crystallized. Fibers must be nontoxic, nonallergenic, and noncarcinogenic and have the ability to sterilize without imparting any change in their physical or chemical characteristics.

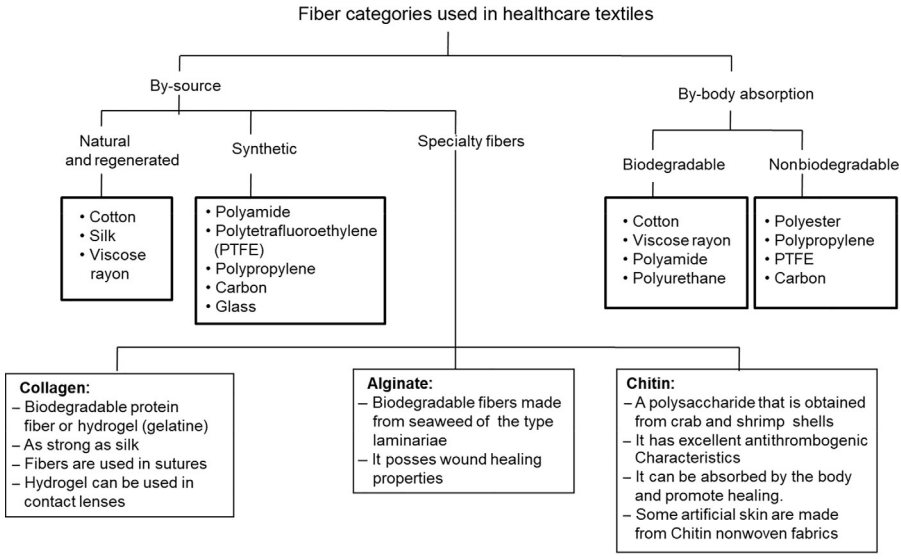


Fig. 16.1 Fiber categories used in health-related applications.

Natural fibers used in medical applications include cotton, long-vegetable fibers, and silk. These fibers are mainly used in nonimplantable products. Regenerated cellulosic fibers are also widely used in nonimplantable products and healthcare/hygiene products. For some special applications, natural fibers can be treated by chemicals to enhance their performances. For example, microbiocidal compositions that inhibit the growth of microorganisms can be applied onto natural fibers as coatings. Most synthetic fibers are used for implantable and other high-performance medical products. Commonly used synthetic materials include polyester, polyamide, polytetrafluoroethylene (PTFE), polypropylene, carbon, and glass. Again, microbiocidal compositions that inhibit the growth of microorganisms can be incorporated directly into these fibers.

When body absorption is of primary concern, the extent of fiber biodegradability becomes a critical aspect in the development of health-related products. Biodegradable fibers are those that can be absorbed by the body within 2–3 months after implantation [2]. These include cotton, viscose rayon, polyamide, polyurethane, collagen, and alginate. Fibers that are slowly absorbed within the body and take more than 6 months to degrade are considered as nonbiodegradable. These include polyester, polypropylene, PTFE, and carbon.

Specialty fibers are those developed specifically to be absorbed in the human body shortly after medical applications. Examples of these fibers that have been proved to contribute significantly to the healing process include collagen, alginate, and chitin fibers [1–4]. Collagen fibers are commonly used as sutures for surgery inside the human body. Collagen is a protein substance obtained from bovine skin and available in either fiber or hydrogel (gelatin) form. The fibers can be used as sutures because of

their strength and biodegradability. The transparent hydrogel, formed when collagen is cross-linked in 5%–10% aqueous solution, has high oxygen permeability and can be processed into soft contact lenses. Calcium alginate fibers are used for wound dressing due to their nontoxicity and hemostatic properties as well as their biodegradability [5]. These fibers are produced from seaweed of the type *Laminaria*. Chitin is a polysaccharide obtained from crab and shrimp shells [2]. It has excellent antithrombogenic characteristics and can be absorbed by the body. Chitin nonwoven fabrics can be used as artificial skin due to their ability to adhere to the body, assisting new skin formation that accelerates the healing rate and reduces pain. When chitin is treated with alkali, it yields chitosan, which can be spun into filaments of similar strength to viscose rayon.

The development of fibers suitable for medical applications is likely to continue for many years as a result of the wide variety of medical applications and the continuing needs for fibers that meet critical health-related criteria such as biodegradability, biocompatibility, and biosafety. Waste disposal and environmental friendliness have also become essential criteria for such materials. The naturally derived fibers mentioned earlier (collagen, alginate, and chitin fibers) are now used in many applications. More fibers of natural sources are being developed. For example, polylactic acid or polylactide, generically known as PLA fiber, is derived from natural raw materials (starch and cellulose) and is completely biodegradable. Researchers in Japan have used poly-L-lactic acid (PLLA) fibers for developing drug delivery system for surgical implants. Medical textile research groups at the Institute of Textile Technology, RWTH, Aachen, were able to spin polyvinylidene fluoride (PVDF) and poly-D-lactic (PDLA) multifilaments, which can be converted into staple fibers to make needle-punched nonwovens for scaffolds for tissue regeneration of periodontal defects. In addition, nanofibers are likely to have a solid place in medical applications leading to new directions of development of medical fibers.

16.2.2 Fibrous structures used for health-related products

All basic fibrous structures are used in the design of medical textiles. These include woven, knitted, braided, and nonwoven structures. Among all the fibrous structures used, nonwovens represent a significant portion in health-related products. This is directly a result of the fact that a high percentage of these products are disposable or short lived. Nonwoven structures can be made into a wide variety of products including [5, 6] operating room apparel (e.g., surgical packs, pants, and gowns), operating accessories (e.g., caps, masks, shoes, and covers), gauze replacements (e.g., sponges and bandages), sterilization wrap used as barrier against air and waterborne bacteria, disposable bedding, and incontinence products (e.g., pads, liners, protective underwear, and wipes).

In addition to the economic aspects associated with making nonwovens, particularly in comparison with making costly woven or knit structures, nonwovens allow unlimited options of design to meet healthcare functions. These include [5, 6] different raw material selections or blends, different ways of web formation, different bonding techniques, and different possibilities of blending fibrous with nonfibrous materials to form nonwoven composite structures. These design options can result in a wide range

of weight, strength, flexibility, and comfort. For example, nonwovens can be made of light weight, 5–15 g/m^2, which is important for many healthcare products such as tissues, transmission, barrier, or wicking layers in composites. Heavier nonwovens are used in absorbent dressings, incontinence use, insulation, and filtration. They can also be strong for durable products such as slings or moderately strong for products such as padding bandages. When filtration and protection are required, nonwovens can be made unstretchable (low elongation), and when support and retention are required, they can be made stretchable and of high elastic recovery.

Perhaps, the most critical performance characteristic of nonwovens is controlled wetting and fluid absorbency. In this regard, nonwovens can perform in many ways depending on the raw material used, the structural density, and the type of finish used. Nonwovens can also be made of a wide range of thermal properties from highly insulative, which is good for wound dressing to avoid heat loss, to moderate insulation associated with good breathability. As filters, nonwovens can also be made of different levels of pore size and pore distribution depending on whether large particles or small particles need to be isolated.

In the healthcare field, many forms of composite nonwovens have been developed over the years and for various applications. These include [5, 6] (a) padding layers (for absorbency, super absorbency, and thermal/mechanical insulation and protection), (b) barrier layers for the prevention of liquid bacterial strike through, and (c) carrier layers for other materials such as superabsorbent powders, activated carbon, antimicrobials, adhesives, and microspheres.

Knit fabrics represent another common fibrous structure used in medical textiles [2–4]. As indicated in Chapter 10, knit structures are different from woven structures in many aspects. Knit fabrics have looser structure, high flexibility, and high porosity. Stretch and elasticity yield an ease of manipulation that is often required in medical applications. In medical dressing applications, it is important to insulate and prevent trauma, attach the drugs to the wound, and absorb liquids. Wound dressings should, therefore, exhibit key characteristics such as good hygroscopicity, good breathability, and comfortable sensation when it comes in contact with the skin. Knit structures assist in these characteristics through high extensibility, elasticity, better fitness, and flexibility.

In injury-support applications, tubular weft-knit structures can provide support to strained areas of the body such as ankle, elbow, or knee or where bandages or heat packs need to be kept in place. Tubular knits can be made in various diameters depending on the application considered. The use of spandex in medical tubular knits can provide many design options. Spandex yarns used in medical tubular knits are often double covered with spandex fiber in the yarn core, and two layers of fiber wrapper (e.g., nylon) are used, one in the clockwise direction and the other in the counterclockwise direction. The first layer controls fabric stretch, and the second layer balances any potential for the yarn to torque. Tubular knits made from double covered yarns also exhibit high abrasion resistance. In some tubular structures, a false twist textured top layer of yarn with lower stretch properties produces a smoother yarn.

Warp-knit structures such as pillar stitch and tricot stitch are used in medical bandages. They are also used in medical implants including vascular grafts, ligaments,

heart valve components, hernia mesh fabrics, and adhesion barriers. In some applications, knitted polyester vascular and cardiovascular grafts possess a tricot fabric with a velour surface that is designed to promote tissue growth. Warp-knit structures are also used to knit artificial blood vessels using double-needle-bar warp-knitting machine with more patterns and ground bars with tricot stitch and atlas stitch being generally used. Warp-knit pillar stitch, tricot stitch, and atlas stitch are also used for hernia mesh applications. These structures have higher strength and greater stability. The materials used in these applications include polyester, polypropylene, expanded polytetrafluoroethylene (ePTFE), polyvinylidene fluoride, and absorbable polymers polyglycolic acid.

Woven structures are used in numerous medical textiles including wound care absorbent pads, bandages, orthopedics, plasters, gauzes, and lint. Woven grafts are made of plain, twill, and satin weaves. Other weave patterns used in the medical field include leno weave, pile fabrics, and velvet/spacer. Key performance characteristics of these grafts are surface smoothness, handling ease, nonreactivity, water permeability, bursting strength, suture retention strength, and biological healing response. More woven structure applications in the medical field will be discussed in the following sections.

Braid structures are also used in medical textiles. Recall that braiding is based on intertwining of three or more yarns to make a fabric. Medical fabrics are formed by interfacing the yarns diagonally to the production axis of the material. The major variables in braided products are the numbers of elements (yarns, wires, and combinations of both), the braid angle, and the number of crossings per inch (density). These factors provide many design options to produce products of widely differing physical and mechanical properties. Braids can also be produced in multiple configurations including solid braid, hollow core braid, multilayer braid, flat braid, and bifurcated/trifurcated/quadfurcated braid.

16.2.3 Categories of medical textiles

In general, fibrous structures utilized in medical textiles will largely depend on the type of product used and its anticipated functions. In this regard, four main categories of products should be considered [1–4]: (a) nonimplantable products, (b) implantable products, (c) extracorporeal devices, and (d) healthcare/hygiene products.

16.2.3.1 Nonimplantable products

Nonimplantable products are typically used to provide protection against infection, absorb blood and exudates, and promote healing. The term nonimplantable is used to generally indicate surface wound treatments at different parts of the human body. This makes items such as wipes and swaps also included in this category. However, the main products of this category are wound dressings or gauzes and bandages.

Wound dressings are used in the medical field to provide critical functions that collectively aim at promoting wound healing. These functions are [7–10] protection, absorption, compression, immobilization, and aesthetics. Protection is the primary

function of wound dressing since exposed wounds can be subjected to further trauma and additional tissue loss caused by external forces (i.e., severe environments, touching objects, or direct interaction). Wound dressing acts as a barrier against these forces. The fact that most open wounds generate blood and exudates requires wound dressing that can absorb these substances to reduce the risk of bacterial proliferation and subsequent infection. A key aspect of the absorption function is a quick release of these liquid substances so that they do not accumulate in the interface between the skin and wound dressing. This is achieved through a combination of wicking and absorption mechanisms. Covering the wound entirely with wound dressing often involves undesirable compression against the open wound. It is important, therefore, that the wound dressing provides a cushioning feel rather than a pressing feel to the wound. Immobilization is also a key function in some wounds as tissue movement can delay the healing process. Finally, wound appearance and aesthetics have become important as wounds naturally draw people's attention. In this regard, wound dressing should appear neat and tidy, particularly on the outer surface.

Most wound dressings consist of multiple layers of components that assist in promoting wound healing [2, 7]. As shown in Fig. 16.2, the first layer is the direct-contact layer. This layer should not adhere to the wound and should allow an easy removal of the wound dressing without disturbing new tissue growth. This layer may be made from very light knitted, woven, or nonwoven structure using fibers such as silk, polyamide, viscose, or polyethylene. Nonadherence is typically achieved by the nature of the fabric structure and/or using nonadhesive coating material. The next layer should attract any drainage that might exude from the wound. This is achieved through the use of an absorbent pad that provides a combination of wicking and absorption. This pad is typically made from cotton or viscose nonwoven structure. The final layer is a flexible diffusion layer attached to the absorbent pad by an adhesive.

In most situations, the direct-contact wound dressing is wrapped by other dressings such as soft gauze rolls to secure it in place. One of the common dressings is nonelastic roll gauze. Stability can be provided to this dressing by reinforcement with adhesive tape. Obviously, as more layers are added, compression may escalate, and this should be avoided. When additional immobilization is required, a plaster splint or

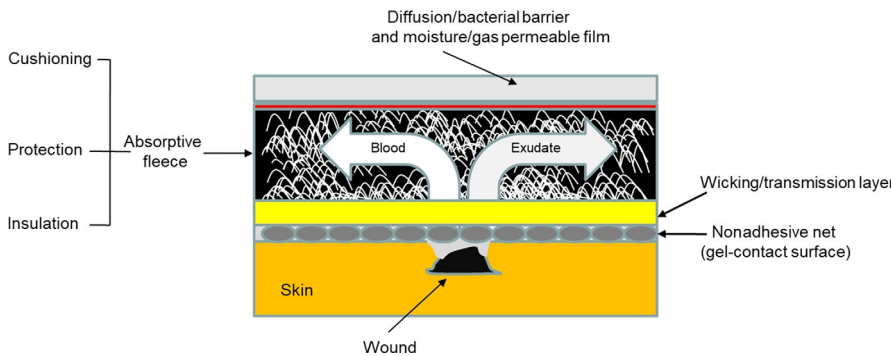


Fig. 16.2 Basic structure of wound dressing laminate.

prefabricated splint might be required. This should be well padded so that additional adverse pressure is not provided.

Other wound dressing products include gauze, lint, and wadding. Gauze is an open weave of absorbent structure that, when coated with paraffin wax, is used for the treatment of burns and scalds. For surgical applications, gauze serves as an absorbent material when used in pad form (swabs). Lint is a plain weave cotton fabric that is used as a protective dressing for first-aid and mild burn applications. Wadding is a highly absorbent material that is covered with a nonwoven fabric to prevent wound adhesion or fiber loss.

It should be pointed out that no single dressing is suitable for all types of wounds and a combination of different types of dressings may be used during the healing process of a single wound. Since 1990s, many new synthetic dressings have been introduced. These include [7–10] vapor-permeable adhesive films, hydrogels, hydrocolloids, alginates, synthetic foam dressings, silicone meshes, tissue adhesives, barrier films, and silver- or collagen-containing dressings. The development of wound dressing products has been based on clear understanding of the specific healing function of the product. In this regard, wound dressings can be classified into three broad categories [7–10]: passive dressing, interactive dressing, and biointeractive dressing. A passive dressing represents the simplest and least expensive structure as it primarily aims at providing a cover over a wound. An interactive dressing is typically a polymeric film, which is typically transparent, permeable to water vapor and oxygen, and nonpermeable to bacteria. Examples of this type of dressing include hyaluronic acid, hydrogels, and foam dressings. A biointeractive dressing is a structure that not only can deliver the functions of the simple and interactive dressings but also can deliver substances active in wound healing, for example, hydrocolloids, alginates, collagens, and chitosan.

Bandages are familiar products that are used in many medical applications, primarily to hold dressing in place over wounds [2–4]. They can be made in many different forms such as woven, knitted, or nonwoven fabrics using cotton or viscose fibers. The fabrics are typically cut into strips then scoured, bleached, and sterilized. Some bandages should exhibit elastic and stretch characteristics so that when applied under enough tension, the recovery of stretch provides support to sprained limbs. Bandages used for simple applications can be nonelastic. Some bandages are made in knitted tubular form of different diameters. These are inherently elastic and stretchy. Most woven bandages are used for light support in the management of sprains or strains. In this case, the elastic nature of the fabric is induced by weaving cotton crepe yarns of high twist levels or by weaving two warp yarns at different tension levels. For applications such as the treatment and prevention of deep vein thrombosis, leg ulceration, and varicose veins, compression bandages are used. These bandages are designed to exert certain levels of compression on the body when applied at a constant tension. For leg and ankle treatments, compression bandages are classified by the amount of compression they can exert at the ankle into extra-high, high, moderate, and light compression. These types of bandages can be made from tubular or customized knitted fabrics or from woven fabric that contains cotton and elastomeric yarns. Another type of bandages is the so-called orthopedic cushion bandages. These are used under

plaster casts and compression bandages to provide padding and prevent discomfort. Some nonwoven orthopedic cushion bandages are produced from either polyurethane foams, polyester, polypropylene fibers, or blends of natural and synthetic fibers. In this regard, loftiness and bulkiness are key characteristics that can be controlled using light needle punching.

Key performance characteristics of nonimplantable products, particularly wound dressings, are shown in Fig. 16.3. Any wound dressing should maintain a moist environment at the wound/dressing interface and should absorb excess exudate without leakage to the surface of the dressing [9–12]. In addition, wound dressing should provide thermal insulation, mechanical, and bacterial protection. These characteristics can be optimized using numerous design parameters reflected in the various attributes of the fibrous elements used for making nonimplantable products. As indicated earlier, the key parameter is fiber type. This is the parameter that will determine the extent of biodegradability, the mechanical properties of the product (strength and elasticity), the absorption or wicking characteristics, and the weight of the product. As fibers are transformed into yarns and fabrics, key attributes that contribute largely to the performance of nonimplantable are largely structurally related as illustrated in Fig. 16.3.

The performance characteristics listed in Fig. 16.3 and their associated attributes should be viewed on the basis of the wound-related criteria as specified by medical experts [7, 10]. These criteria may include the type of wound, size of wound, location of wound (poor vascular areas or areas under tension heal slower than areas that are highly vascular), age of wound (fresh surgical wounds vs. chronic wounds), presence of wound contamination or infection (bacterial contamination that slows down the healing process), age of the patient (the older the patient, the slower the wound heals),

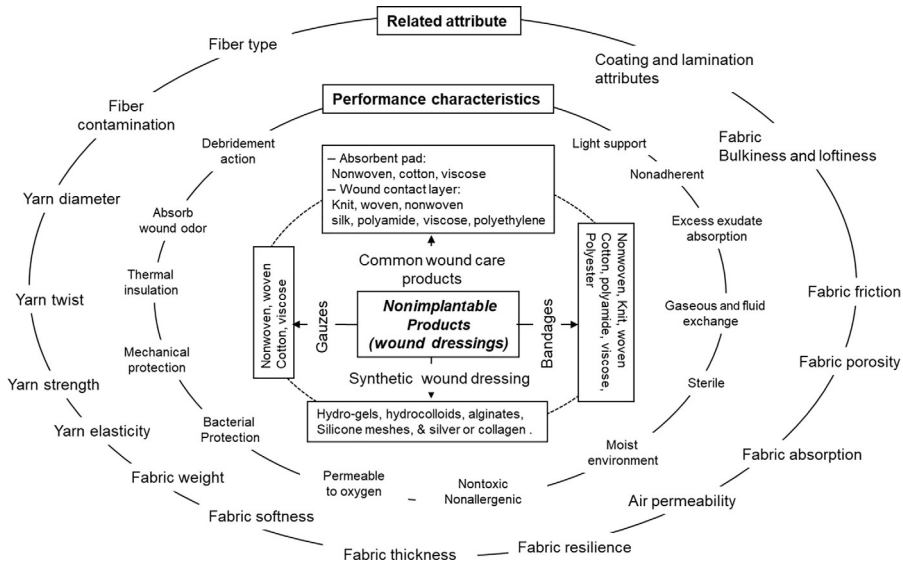


Fig. 16.3 Performance characteristics and related attributes of nonimplantable products.

general condition of the patient (malnutrition that slows down the healing process), and medication (e.g., antiinflammatory drugs that may slow down the healing process). Failure to account for these criteria can result in products that are highly liability and safety questionable.

16.2.3.2 Implantable products

Implantable products, often called biomaterials, are used to assist in wound closure (e.g., sutures) or replacement surgery (e.g., vascular grafts and artificial ligaments). In recent years, a dramatic increase has occurred in the number of implantable products in which numerous types of biomaterials were utilized. Many of these products have become common in most operation rooms. Descriptions of different implantable products are presented in many literatures [2–4, 11–17]. Among all implantable products, sutures represent the most commonly used products. Sutures used for wound closure can be made from monofilament or multifilament yarns [11–17]. For internal wound closures, biodegradable sutures should be used. These can be made from monofilament braided collagen, polylactide, and polyglycolide. For closing exposed wounds, nonbiodegradable and removable sutures can be used. These can be made from monofilament braided polyamide, polyester, PTFE, and polypropylene.

Another important category of implantable products is soft tissue implants [2, 3]. These are flexible and strong materials commonly used for the replacement of tendons, ligaments, and cartilage in both reconstructive and corrective surgery. Artificial tendons are typically inelastic cords or bands of tough white fibrous connective tissue that attach a muscle to a bone or other part. They are typically made from woven or braided porous meshes or tapes surrounded by a silicone sheath. During implantation, the natural tendon can be looped through the artificial tendon and then sutured to itself to connect the muscle to the bone. Implantable materials used to replace damaged knee ligaments (anterior cruciate ligaments) include braided polyester artificial ligaments and braided composite materials containing carbon and polyester filaments. Cartilage is a tough elastic tissue that is found in the nose, throat, and ear and in other parts of the body and forms most of the skeleton in infancy, changing to bone during growth. Some cartilages are hard and dense (e.g., hyaline cartilage). These typically contain no flexible fibers as rigidity is important for this material. Others are elastic and flexible and provide protective cushioning. Low-density polyethylene is used to replace facial, nose, ear, and throat cartilage. Carbon fiber-reinforced composite structures are used to resurface the defective areas of articular cartilage within synovial joints (e.g., knees) as a result of osteoarthritis.

Orthopedic implants are typically used for hard tissue applications to replace bones and joints [2, 3]. Fixation plates can also be considered under this category; these are used to stabilize fractured bones. For these components, fiber-reinforced composite materials are the best candidates as they can be designed to meet biocompatibility and high strength requirements. Traditionally, metal implants have been used for these applications. One of the advantages of using fibrous materials in these applications is the promotion of tissue ingrowth around the implant using a graphite and

PTFE (e.g., Teflon) nonwoven mat. This acts as an interface between the implant and the adjacent hard and soft tissue.

Another category of implantable products is the so-called cardiovascular implants (or vascular grafts). These are used in surgery to replace damaged thick arteries or veins. Materials used in this category include [2, 3] knitted or woven constructions made from polyester or PTFE structures. Knitted fabrics are useful because of their flexibility and porous structures that allow the graft to become encapsulated with new tissue. However, porosity can also allow blood leakage (hemorrhage) through the pores after implantation. Woven structures, on the other hand, can be made of lower porosity, but this can hinder tissue ingrowth. Artificial blood vessels with an inner diameter of 1.5 mm have been developed using porous PTFE tubes, which consist of an inner layer of collagen and heparin to prevent blood clot formation and an outer biocompatible layer of collagen with the tube itself providing strength. Artificial heart valves, which are caged ball valves with metal struts, are covered with polyester fabrics to provide a means for suturing the valve to the surrounding tissue [2–4].

Fig. 16.4 illustrates key performance characteristics of implantable products and associated attributes. The most critical challenge associated with the design of implantable products is body compatibility, or biocompatibility. From a medical viewpoint, an implantable product should be developed in view of the tissue bed in

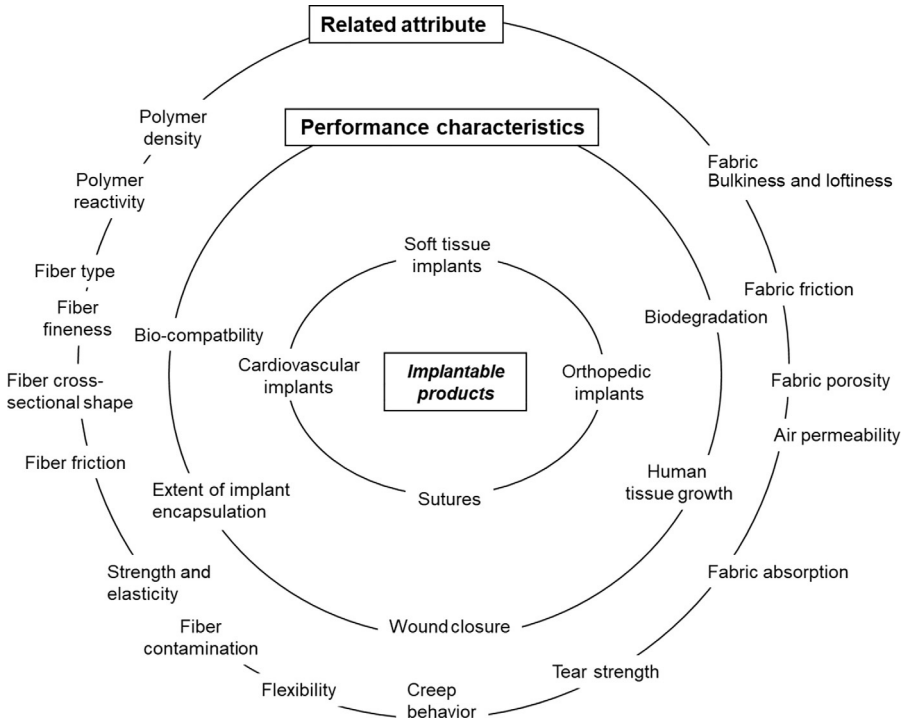


Fig. 16.4 Performance characteristics and related attributes of implantable products.

which it is placed [3, 4]. The simplest definition of body tissues is that it is a layer or group of similarly specialized cells that conjointly perform certain functions. There are many different types of tissues throughout the body, and they differ markedly in composition, structure, strength, and function. Body skin and many internal parts exhibit very soft tissues that have to be treated carefully when wound closure products such as sutures are used. In this regard, critical design aspects should include biocompatibility, biomaterial tensile strength, flexibility, and tear resistance in reference to tissue strength. It should also be pointed out that even within the body soft tissues, some are stronger than others. For example, bladder tissues are relatively weaker than skin tissues.

Safety and side effects represent key aspects that should be associated with implantable products, particularly when biocompatibility is of a major concern. The implantation of biomaterials may initiate both an inflammatory reaction to injury and mechanisms to induce healing. For instance, implantation of nonresorbable biomaterials can cause a permanent alteration in the microenvironment surrounding the implant and in the tissues into which they are implanted. The extent to which the inflammatory reaction and healing mechanisms are activated is a measure of the host reactions to the biomaterial and ultimately may lead to impairment of functional capacity or permanent biocompatibility of the implant [2–4]. It is important, therefore, to develop an accurate understanding of the biological response to implantable products or biomaterials.

The reaction of human body to implantable substances is determined by a number of key attributes. The most important factor is porosity, which determines the rate at which human tissue will grow and encapsulate the implant. Fiber fineness is another key factor with small and uniform diameters being better in terms of encapsulation with human tissue. Toxicity is also an important factor as it can dangerously influence body reaction to implantable products. A release of toxic substances such as harmful chemicals and lubricants and finish by the fiber polymer can be fatal. Finally, biodegradability should be considered in any implantation application.

Since sutures represent the largest volume of implantable products, it will be useful to dwell on their performance characteristics. A suture is defined as a thread that can perform one of two functions [11–17]: (a) joins adjacent cut surfaces of the wound through replicating and maintaining tissues until the natural healing process has provided sufficient level of wound strength and (b) compresses blood vessels to stop bleeding. As indicated earlier, sutures used for wound closure can be made from monofilament or multifilament yarns. For internal wound closures, biodegradable sutures should be used. These are commonly called absorbable sutures as they do not have to be removed and they are absorbed or decomposed by body reactions such as hydrolysis. For closing exposed wounds, nonbiodegradable, also called nonabsorbable, can be used. Figs. 16.5 and 16.6 illustrate examples of these two types of sutures.

By the nature of their basic functions, surgical sutures should exhibit a number of key performance characteristics (see Fig. 16.7): absorption rate, strength loss, and tissue reaction for absorbable sutures and strength, knot security, and tissue reaction for nonabsorbable sutures. Design efforts to meet these characteristics have been

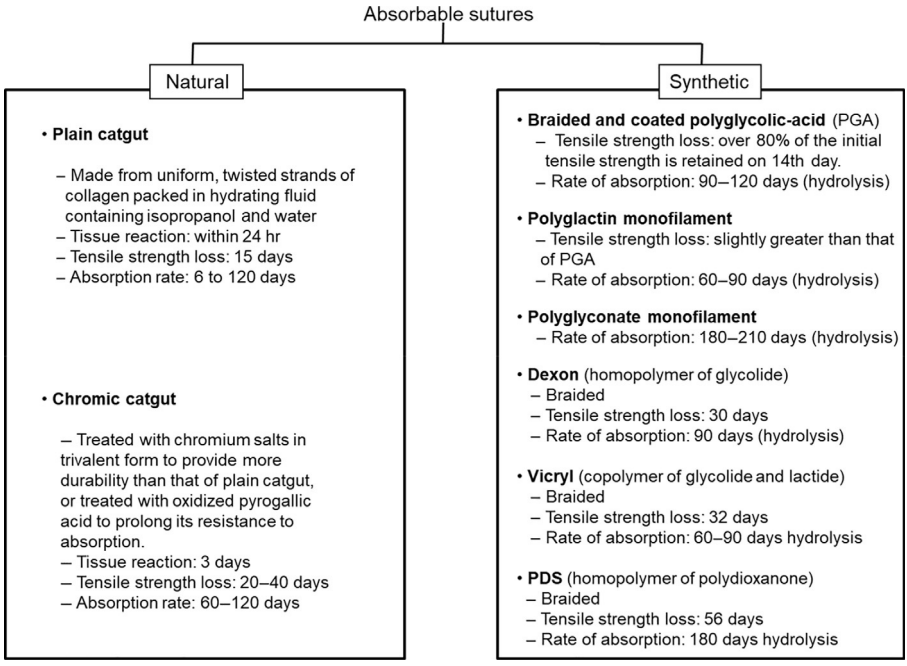


Fig. 16.5 Classifications of absorbable sutures.

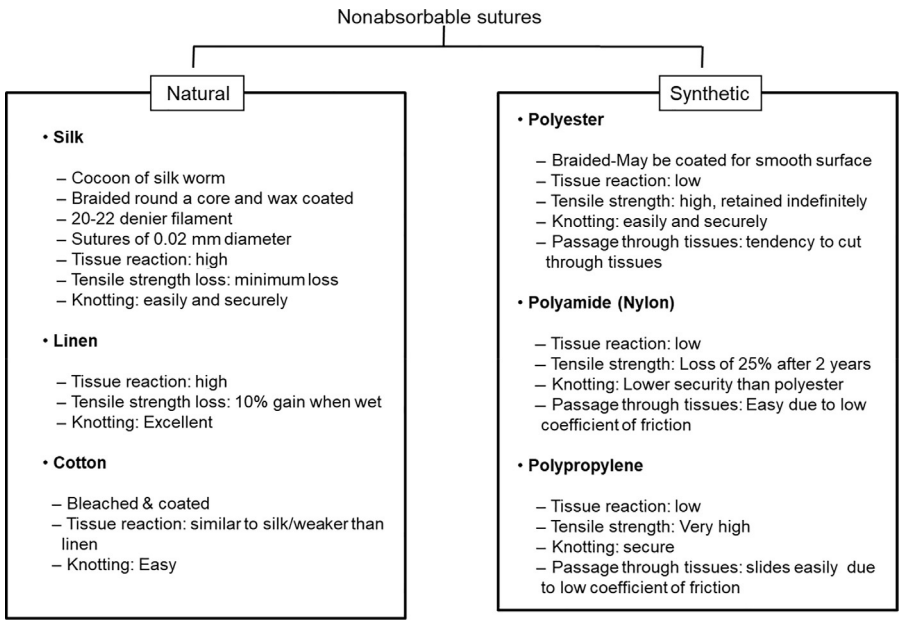


Fig. 16.6 Classifications of nonabsorbable sutures.

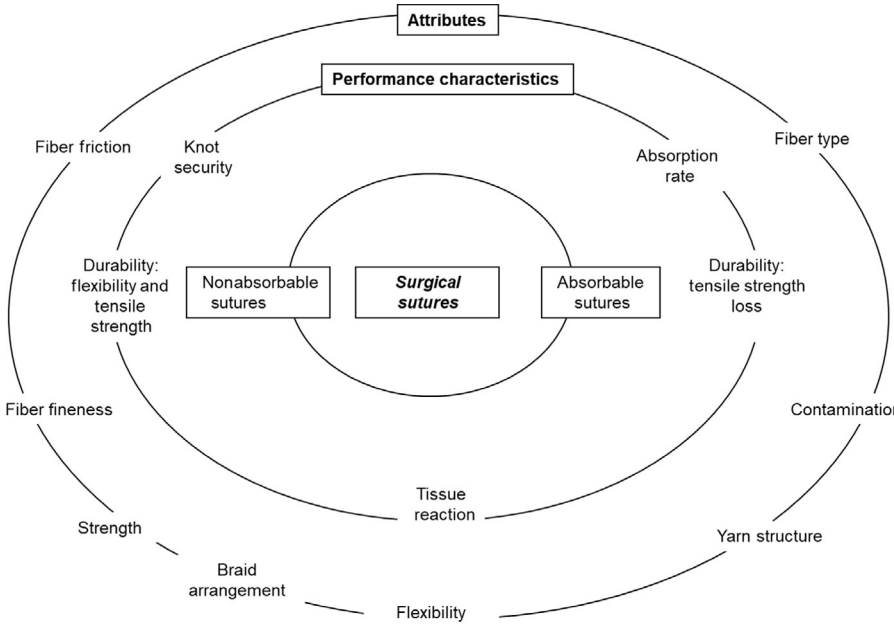


Fig. 16.7 Performance characteristics and related attributes of surgical sutures.

focused on critical aspects such as (a) for braided yarns, improving the structure of the braids (e.g., spiral vs. lattice braided materials); (b) for core/sheath yarns, reducing the difference in the elongation properties between the core and the sheath yams and using finer denier filaments in the sheath yams; and (c) for knot performance, improving knot security and performance (e.g., exposing a two-throw square knot to laser beam energy).

16.2.3.3 Extracorporeal devices

Fig. 16.8 illustrates the main examples of extracorporeal devices, their performance characteristics, and associated attributes. Extracorporeal devices are mechanical organs that are primarily used for blood purification. They include [2, 3] the artificial kidney (dialyzer), the artificial liver, and the mechanical lung. The function of an artificial kidney is achieved by circulating the blood through a membrane that retains the unwanted waste materials. This membrane may be either a flat sheet or a bundle of hollow regenerated cellulose fibers in the form of cellophane. Waste material can also be removed using multilayer filters composed of numerous layers of needle-punched fabrics with varying densities. The artificial liver utilizes hollow fibers or membranes similar to those used for the artificial kidney to perform their functions. The microporous membranes used for mechanical lungs possess high permeability to gases

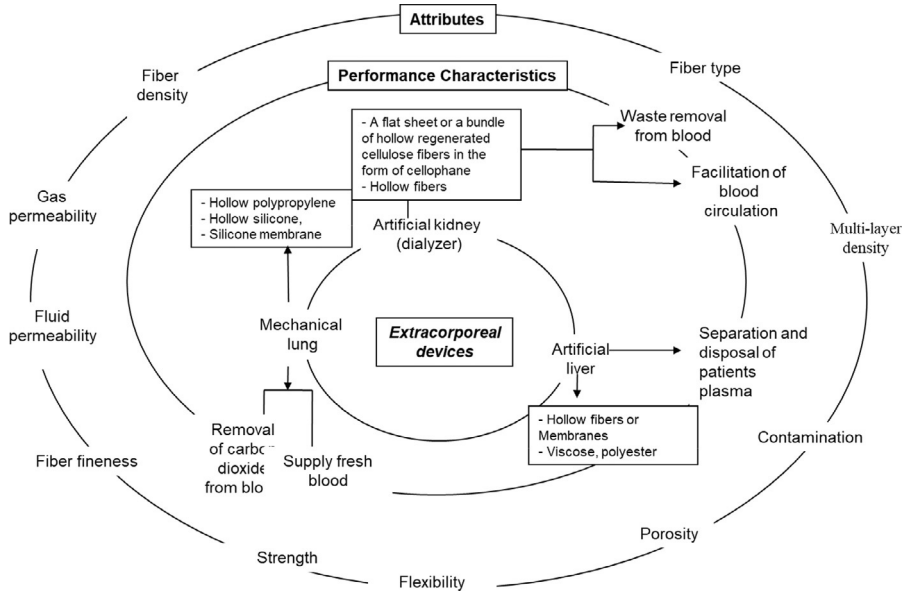


Fig. 16.8 Performance characteristics and related attributes of extracorporeal devices.

but low permeability to liquids and function in the same manner as the natural lung allowing oxygen to come into contact with the patient's blood.

16.2.3.4 Healthcare and hygiene

Fig. 16.9 illustrates the main examples of healthcare and hygiene products, examples of their performance characteristics, and some associated attributes. Healthcare and hygiene products include [2] hospital gowns and uniforms, clothing and wipes, surgical covers, masks, caps, and hospital bed products. These products should exhibit a number of key characteristics such as cleanness, contamination free, and infection control. In a typical hospital's environment, infection represents a critical issue as it can result in further complications in patient's conditions [2]. For this reason, traditional muslin materials have been replaced by barrier materials in hospitals in many developed countries. Pollutant particles shed by hospital staff may carry bacteria that can result in an infection to the patient. Hospital gowns, particularly in surgery rooms, should be designed in such a way that they can prevent the release of pollutant particles into the air. As a result, the fiber material and the fabric structure of these gowns should be carefully selected so that they do not act as dust and contamination traps and they do not easily release these particles to the surrounding. In this regard, most surgical gowns are made from disposable nonwoven fabrics.

Surgical masks should be of light weight, and they should have a high filter capacity and high level of air permeability. A typical surgical mask will consist of a three-layer structure [3]: outer and inner layers made from acrylic-bonded parallel-laid or

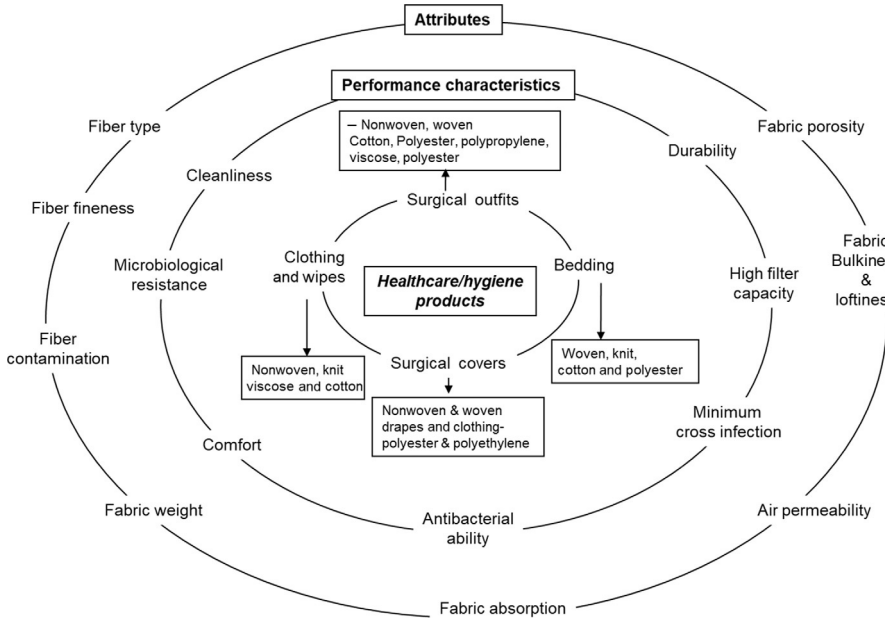


Fig. 16.9 Performance characteristics and related attributes of healthcare/hygiene products.

wet-laid nonwoven and a very fine middle layer of extra-fine glass fibers or synthetic microfibers. Disposable surgical caps are usually parallel-laid or spun-laid nonwoven materials based on cellulosic fibers.

Operating room disposable products and clothing include [2] surgical drapes and cover cloths that are used in the operating room either to cover the patient (drapes) or to cover working areas around the patient (cover cloths). Nonwoven structures are used extensively for drapes. Cover clothes are typically composed of films that are completely impermeable to bacteria, backed on either one or both sides with nonwoven fabrics that are highly absorbent to both body perspiration and secretions from the wound. Bacteria barrier characteristics are also achieved using hydrophobic finishes. Another development in surgical drapes is the use of loop-raised warp-knitted polyester fabrics that are laminated back to back and contain microporous PTFE films in the middle for permeability, comfort, and resistance to microbiological contaminants. Most hospital blankets are made from cotton leno woven structures to reduce the risk of cross infection. The yarns used are typically soft-twisted, twofold yarns to provide desirable durability, good hand, and appropriate thermal characteristics and can easily be washed and sterilized.

Disposable diapers used in hospitals typically consist of a three-layer composite article [5, 6]: (1) an inner covering layer, which is either a longitudinally orientated polyester web treated with a hydrophilic finish or a spun-laid polypropylene nonwoven material; (2) an absorbent layer; and (3) an outer impermeable layer.

16.3 Protective textiles

The concept of protection of human being has evolved over the years from merely a protection against Mother Nature and wild animals to a protection against numerous hazardous sources, most of which are created by humans as a result of the many requirements of modern life. Over the duration of this evolution, fibrous products have contributed immensely to the protection of human being. Today, numerous protection systems are available for use by human both in regular living and in the workplace. These systems may be divided into two main categories: protective clothing and protective gears. The term "protective clothing," which refers to clothing items used specifically for protection, is often used interchangeably with the term "protective gear," which refers to more general forms of protective systems including helmets, masks, guards, and shields. Examples of protective clothing and protective gears are listed in Tables 16.1–16.4. These include protective garment systems, body armors, body protection systems (arm/shoulder protection and gloves), and protective masks.

The extent of protection provided by fibrous products will primarily depend on three main factors [18, 24]: (a) the hazardous source, (b) the extent of danger (applications), and (c) the time of exposure. At the extreme levels of these factors, a single

Table 16.1 Examples of protective garment systems [18–21].

Protective system	Purpose	Material
Hazmat suits	• A fully encapsulating garment worn as protection from hazardous materials or substances • It is generally combined with breathing apparatus or protection and may be used by firefighters, emergency personnel responding to toxic spills, researchers, or specialists cleaning up contaminated facilities	• It can be made from various materials and fibers that have inherent capabilities of resisting chemical, nuclear, or other hazardous substances • Fibers can also be treated with appropriate barrier materials to perform these protective functions • Examples of material include fluoropolymer (e.g., Teflon PTFE)
Space suites	• A complex system of garments, equipment, and environmental systems designed to keep a person alive and comfortable in outer space • Basic criteria of a space suit are stable internal pressure; mobility; breathable oxygen;	Different materials which are used to make spacesuit are as follows: • Nylon tricot • Spandex • Urethane-coated nylon • Dacron • Neoprene-coated nylon • Mylar

Table 16.1 Continued

Protective system	Purpose	Material
	temperature regulation; shielding against ultraviolet radiation; protection against small micrometeoroids; a communication system; means to recharge and discharge gases and liquids; means to maneuver, dock, release, and/or tether onto space craft; and means of collecting and containing solid and liquid waste	• Gore-Tex • Kevlar • Nomex

Table 16.2 Examples of body armor protective systems [22, 23].

Protective system	Purpose	Material
Soft vests	• Soft, flexible, and less bulky vests • It is more likely to be worn underneath a uniform or in addition to some other kind of gear • In some cases, soft armor is used in conjunction with hard armor to provide the user with as much protection as possible • They are commonly worn by police forces, private citizens, and private security guards • Protect wearers from projectiles fired from handguns, shotguns, and shrapnel from explosives such as hand grenades	• Kevlar • Spectra • Twaron
Hard body armor	• Consists of a soft armor shell situated with metal plates, typically made of ballistic steel or ceramic • The plates are integrated into functional apparels • Hard body armor is far stronger than soft body armor because of its impenetrable internal plates	• Kevlar • Ceramic or metal plates inserts

Continued

Table 16.2 Continued

Protective system	Purpose	Material
	• Many kinds of hard armor utilize layered plates made of ceramic. These plates are also coated in a strong protective material for additional strength • Because of its strength qualities, hard armor is heavier and less pliable than soft body armor • Discomfort is of great concern with this type of body armor	
Interceptor body armor system	• Used for military combats • Typically made of two modular components: the outer tactical vest and small arms protective inserts or plates • Webbing on the front and back of the vest permits attaching such equipment as grenades, walkie-talkies, and pistols	• The outer tactical vest consists of a Kevlar weave aiming at stopping 9 mm pistol rounds • The small arms protective insert (SAPI) is made of a boron carbide ceramic with a spectra shield backing (extremely hard material) • It stops, shatters, and catches any fragments up to a 7.62 mm round with a muzzle velocity of 2750 feet per second • Also, harder than Kevlar

fibrous system may not be sufficient, and a multiple-layer system or alternating specialized systems may be required. In addition, fibrous materials may require special treatments to modify their characteristics, or they may be combined with other materials (e.g., composites or multiple-layer systems) to serve special applications of protection.

With regard to hazardous sources that require human protection, numerous sources can be listed including [18–22] fire, smoke, and toxic fumes; weapons of various types (e.g., ballistic projectiles, nuclear, chemical, and biological); drowning; hypothermia; molten metal; chemical reagents; toxic vapors; foul weather; extreme cold; rain; wind; chemical reagents; nuclear reagents; high temperatures; molten metal splashes; microbes; and dust. The extent of danger will obviously depend on the application in question. Applications or products in which fibrous structures are used for protection are numerous. These include military uniforms, mine-worker clothing, firemen uniforms, policemen uniforms, many sportswear, helmets, tents, sleeping bags, survival bags and suits, heat-resistant garments, turnout coats, ballistic-resistant vests, biological and chemical protective clothing, blast-proof vests, antiflash hoods and

Table 16.3 Examples of shoulder, hand guards, and gloves [18, 19, 24].

Protective system	Purpose	Material
Shoulder pads	A piece of protective equipment used in American football to protect shoulders	• Most modern shoulder pads consist of a shock-absorbing foam material with a hard plastic outer shell. The pieces are usually secured by rivets or strings that the user can tie to adjust the size • A related piece of protective equipment is the rib protector. It attaches to the shoulder pads and wraps around the player's midsection. It is designed to protect the ribs, stomach, and back areas
Hand guards (grips)	• Gymnastics equipment that aid both male and female athletes in artistic gymnastics (e.g., high bar, still rings, and parallel bars) • They can also be used in sports exercises	• Consist of a strip of leather and a wrist strap of either Velcro or a buckle. The strip of leather is about 5 cm across and has finger holes at the top for the third and fourth fingers • Gymnasts normally choose to wear something soft under the wrist strap
Gloves	• Covers the hand of a human • Serve to protect and comfort the hands of the wearer against cold or heat, physical damage by friction, abrasion, or chemicals • They have separate sheaths or openings for each finger and the thumb • If there is an opening but no covering sheath for each finger, they are called "fingerless gloves" • Fingerless gloves with one large opening rather than individual openings for each finger are sometimes called gauntlets • Gloves that cover the entire hand but do not have separate finger openings or sheaths are called mittens • Mittens are warmer than gloves made of the same material because of the extra air inside	• Latex or natural rubber latex • Vinyl or polyvinyl chloride (PVC) • Nitrile or acrylonitrile and butadiene • Polyurethane

Table 16.4 Examples of protective headgears (masks) [18, 19, 24].

Protective system	Purpose	Material
Filter mask	• Protection to the wearer from harmful airborne substances • Usually covers only the mouth and nose. It limits the course of air so that it must flow through a filter that removes harmful dusts or toxic gases	• A dense, fine natural, or synthetic fiber mesh • To aid particulate filtration, the mesh is sometimes coated with substances that enhance the tendency of particulates to adhere to the fibers • For gas filtration, mask cartridges are filled with activated carbon or certain resins to absorb substances such as volatile organic compounds (VOCs), eliminating them from the air breathed
Gas mask	• Worn over the face to protect the wearer from inhaling airborne pollutants and toxic materials • Performs three basic functions: filtration, absorption or adsorption, and reaction and exchange • It forms a sealed cover over the nose and mouth but may also cover the eyes and other vulnerable soft tissues of the face	• Carbon based • Polycarbonate
Surgical mask	• Worn by health professionals during medical operations to catch the bacteria shed in liquid droplets and aerosols from the wearer's mouth and nose • Modern surgical masks are made from paper or other nonwoven material and are discarded after each use	• Wool felt • Fiberglass paper • Polypropylene
SCBA	• Self-contained breathing apparatus, or sometimes referred to as a compressed air breathing apparatus (CABA) or simply breathing apparatus (BA). It is worn by rescue workers such as enforcement personnel and firefighters to provide breathable air in a hostile environment • A SCBA typically has three main components: a high-pressure tank (e.g., 2200–4500 psi), a pressure regulator, and an inhalation connection (mouthpiece, mouth mask, or face mask), connected together and mounted to a carrying frame	• Air cylinders used in these masks are made of aluminum or steel or of a composite construction, usually carbon fiber wrapped, which provides light weight

gloves, molten metal protective clothing, flotation vests, submarine survival suits, immersion suits and dive skins, life rafts, diapers, antiexposure overalls, arctic survival suits, ropes, and harnesses.

Polyethlyene (Tyvek), which is then coated with PE for additional resistance to chemicals This is used for the lightest (C-class) applications.

For higher-stress application, I would think they would coat the cloth in something even more inert—like Teflon—to minimize permeability.

16.3.1 Protection against extreme climate conditions

As discussed earlier, fibrous products can be designed in such a way that provides protection against very hot or very cold weather. Fig. 16.10 illustrates examples of performance characteristics and related attributes for fibrous products used for protection in extreme climates. These are only examples, and they should be made more specific when a protective system is being designed for a specific application.

With regard to hot weather, people in many areas of the world have to endure many days of 90°F plus temperatures every year. When high temperatures are associated with high humidity and high physical activity levels (e.g., military operations, sports, and rescue missions), discomfort becomes a serious issue, and the need for protection becomes a necessity. Basic requirements in a clothing system in this type of environment include dryness (sweat absorption, wicking, and evaporation), coolness (body insulation from surrounding temperature), sun protection, and good tactile properties to allow human to perform high-level physical activities at minimum resistance.

The other extreme of climate conditions is cold or very cold weather. This can be observed at low to extremely low temperatures, and it may be multiplied by rainy or windy conditions. This situation may result in hypothermia, which is a condition occurring when the heat lost from the body exceeds that gained through food, exercise, and external sources. Many approaches have been taken to minimize the effects of hypothermia. These include the use of appropriate insulative clothing and garment components and the use of flotation (in cold water), thermal protection devices, and work wear coveralls that provide buoyancy and thermal insulation in case of accidental and emergency immersions in cold water.

Design for protection against extreme climates should be based on understanding the heat and vapor transfer mechanism of a clothing system. In these environments, clothing should act as a barrier for heat and for vapor transport between the skin and the environment. This barrier is formed both by the clothing materials themselves and by the air they enclose and the still air that is bound to its outer surfaces. In Chapter 12, basic concepts of heat transfer through clothing systems were introduced. The governing equations showing the effect of clothing on heat and vapor transfer are [20]

$$\text{Dry heat loss} = \frac{(t_{sk} - t_a)}{I_T}$$

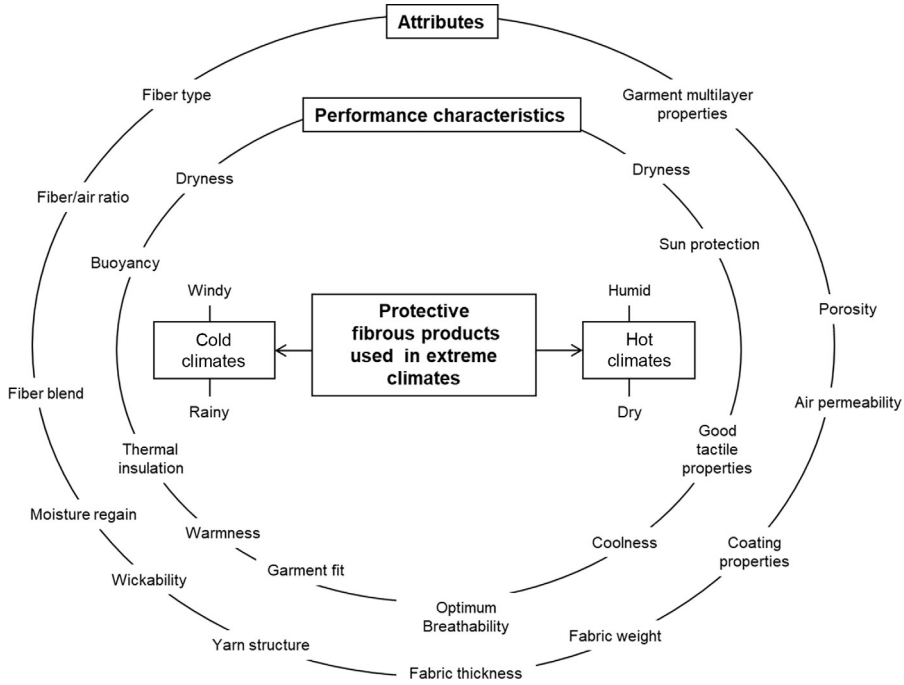


Fig. 16.10 Performance characteristics and related attributes of protective fibrous products used for protection in extreme climates.

where t_{sk} = skin temperature, t_a = air temperature, and l_T = clothing insulation, including air layers.

$$\text{Evaporative heat loss} = \frac{(P_{sk} - P_a)}{R_T}$$

where P_{sk} = skin vapor pressure, P_a = air vapor pressure, and R_T = clothing vapor resistance, including air layers.

As discussed in Chapter 12, the primary modes of heat transfer through clothing systems are conduction and radiation modes. In view of the aforementioned equation, since the volume of air enclosed is typically far greater than the volume of the fibers, factors such as fabric thickness and the amount of entrapped air will represent the most critical design factors associated with thermal insulation. Fiber type, on the other hand, can influence the amount of radiative heat transfer, as certain fibers can reflect, absorb, or reemit radiation.

When the hot environment is also associated with high levels of humidity and high levels of physical activity, the importance of fiber type becomes significant. For example, a clothing system made from 100% cotton is likely to absorb moisture

(sweat), but it will also keep it, slowing the evaporation of sweat (a good cooling mechanism). However, wet clothing will also be inappropriate when temperature goes down as it can result in an undesirable cooling. Accordingly, a cotton/synthetic blend may provide a better alternative, with the natural cotton providing quick absorption of the body sweat and the synthetic material providing a quick release of moisture via a wicking effect so that quick drying and cooling evaporation can occur. However, the role of fiber will largely depend on fabric thickness since thickness also determines the major part of the clothing vapor resistance. Since the volume of fibers is usually low compared with the enclosed air volume, the resistance to the diffusion of water vapor through the garments is mainly determined by the thickness of the enclosed still air layer. Only with thin fabrics, fiber type becomes important as it can affect the diffusion properties more than the thickness of fabric. When coatings, membranes, or other treatments are added to the fabrics, this will have a major effect on vapor resistance since diffusion of vapor molecules becomes an important factor.

When fabrics are made into garments, fabric thickness and fiber type are manifested in a multiple-layer model of skin-garment interface or fabric/fabric/skin interfaces [23] (in the case of multiple-layer garments). In this model, other aspects such as layer thickness, thickness of air attached to fabric surface, and degree of fit (loose or tight fit) become important. In multiple-layer system, the air entrapping capacity between layers becomes a critical design aspect for thermal insulation. In general, each fabric layer will have a still air layer attached to its outer surface. Outside this layer, the air insufficiently bound and will move due to temperature gradients. The nature and the thickness of this air layer are likely to be influenced by a number of factors including fabric surface construction (porosity, surface texture, fiber type, and fabric finish), fabric thickness, and the distance between fabric layers. Therefore, it is expected that for multilayer garments or clothing ensembles, the total insulation will be much higher than could be expected from the insulation of a single fabric layer. In addition, clothing design, body shape, and fit may alter the way fabric layers are separated and, consequently, the amount of still air entrapped in the system. At the shoulders, for example, the layers will be directly touching, and thus, the total insulation will only be the sum of the material layers plus one air layer on the outer surface. When the clothing fits tightly, the ability of entrapping air will largely depend on garment design, but in most situations, less air may be included than when it fits loosely. Also, in the presence of winds, smaller amount of still air will be expected as a result of air movement, garment movement, or wearer body movement.

Protection against extreme climates is most important in military operations. This is particularly true in cold/wet regions, which tend to cause the most severe problems. In these regions, it is critical to achieve and maintain dry thermal insulation. Products that can be affected by these climates include clothing, sleeping bags, and other personal equipment. Again, the key design factors in these systems are the fiber-to-air ratio (or fiber fraction), the fiber arrangement in the overall fibrous structure, and fiber fineness. These factors determine the efficiency of the fibrous insulator. A good insulative fibrous system will typically have a fiber-to-air ratio of 0.1–0.2 (10%–20% of fiber and 80%–90% of air). With regard to moisture, some analysis suggests that the presence of 10%–20% by weight of moisture is sufficient to

cause up to 50% loss in the dry insulation value [18,19]. Fiber arrangement should largely assist in entrapping air in the fibrous structure. Fine fibers can result in accommodation of a larger number of fibers per unit weight of fabric. However, this number should be carefully selected to allow trapping still air in the pores of the fabric structure, leading to high specific surface area, and not to high level of compactness, which can hinder flexibility.

In recent years, numerous fibrous products have been developed for protection against extreme climates. For example, DuPont developed the spun-bonded polyolefin-fiber fabric, Tyvek, aluminized and made into survival suits, survival bags, and many other weather-resistant products. Overalls made from Tyvek primarily aim at thermal insulation. These are useful in cold water situations and can be used by Navy ships and by several airlines flying the polar route in case the aircraft is forced down onto the Arctic ice.

Another example of weather-resistant products is Gentex's Dual Mirror aluminized fabric (see Fig. 16.11), which offers multiple industrial, military, and commercial applications. Specific applications of this fibrous product include industrial heat shielding, molten metal splash protective clothing, radiant heat protective clothing, proximity firefighting, and non-FR infrared heat and sunlight shielding. These applications resulted in the development of a wide range of styles of Gentex's Dual Mirror aluminized fabrics. As shown in Fig. 16.11, this protective fabric consists of five layers: (a) an outer skin of aluminum, (b) a protective film, (c) a second layer of

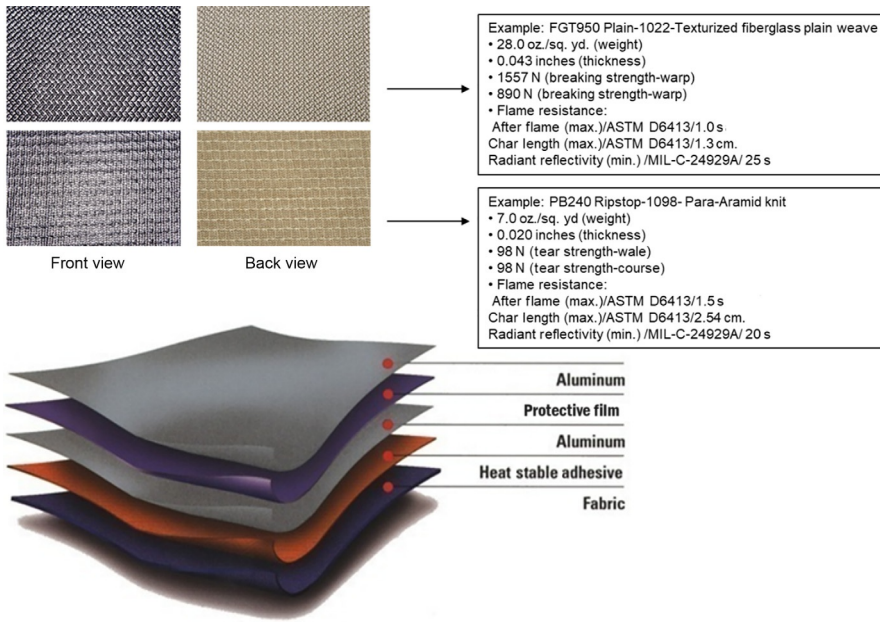


Fig. 16.11 Example of protective fibrous products used for extreme climates Gentex's proprietary Dual Mirror/Flexir aluminized fabric (http://www.Qentexcorp.com).

aluminum, (d) heat-stable adhesive, and (e) a base fabric. These individual layers are then combined to form a single fabric.

16.3.2 Ballistic protection

Fibrous materials have been widely used for developing products that primarily aim at ballistic protection. Fig. 16.12 illustrates examples of performance characteristics and related attributes for fibrous products used for ballistic protection. The idea is that these products should be able to absorb large amounts of energy due to their high tenacity, high modulus of elasticity, and low density [18–23]. The most common fibrous product used for ballistic protection is bulletproof vests. This product is also one of the oldest components of protection used by human over the years. Indeed, throughout recorded history, humans have used various types of materials as body armor to protect themselves from external objects and injuries in combat situations. The first protective clothing and shields were made from animal skins. With the invention of firearms around 1500, other materials including wood and metal shields were also used for protection. Although these materials were effective in their protective aspects, they were too heavy and impractical for high physical actions, fast

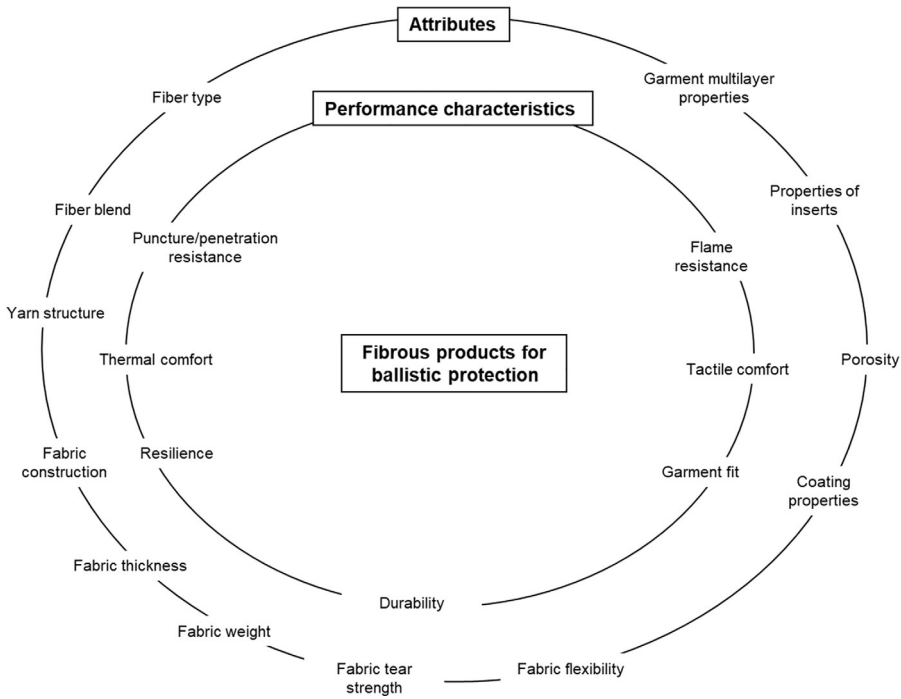


Fig. 16.12 Performance characteristics and related attributes of fibrous products used for ballistic protection.

movement, and battle maneuvering. This has resulted in the development of softer body armors. One of the first recorded instances of the use of soft body armor was by the medieval Japanese, who used armor manufactured from silk. It was not until the late 19th century that the first use of soft body armor in the United States was recorded. At that time, the military explored the possibility of using soft body armor manufactured from silk. The project even attracted congressional attention after the assassination of President William McKinley in 1901. While the garments were shown to be effective against low-velocity bullets (i.e., traveling at 400 feet per second or less), they did not offer protection against the new generation of handgun ammunition being introduced at that time (ammunition that traveled at velocities of more than 600 feet per second). This deficiency associated with the prohibitive cost of silk made the concept unacceptable.

World War II was a turning point in the development of body armor with the introduction of the "flak jacket" made from ballistic nylon. The flak jacket was very cumbersome and bulky. It provided protection primarily from ammunition fragments but was ineffective against most pistol and rifle threats. By the late 1960s, new fibers were discovered that made their ways to today's modern generation of body armors. The invention of Kevlar by DuPont in the 1970s was another significant turning point in the development of body armors (e.g., Kevlar 29). Ironically, the fabric was originally intended to replace steel belting in vehicle tires. In 1988, DuPont introduced the second generation of Kevlar fiber, known as Kevlar 129, which offered increased ballistic protection capabilities against high-energy rounds such as the 9-mm FMJ. In 1995, Kevlar Correctional was introduced, which provided puncture-resistant technology to both law-enforcement and correctional officers against puncture-type threats.

The basic idea of body armor is a simple one. It is based on catching bullet that strikes body armor in a "web" of very strong fibrous assembly [22]. This assembly should absorb and disperse the impact energy that is transmitted to the vest from the bullet, causing the bullet to deform or "mushroom." Additional energy is absorbed by each successive layer of material in the vest, until such time as the bullet is stopped. This principle requires a large area of the garment to be involved in preventing the bullet from penetrating to the body. Unfortunately and despite the great progress of development, no structure exists that will prevent penetration of all ballistic objects, at the same time being wearable and under all situations.

Typical bulletproof vests are made from multiple layers of woven fabric, with the degree of protection is increased as the number of fabric layers increase. These layers are assembled into a "ballistic panel," which is then inserted into the "carrier," which is constructed of conventional garment fabrics such as nylon or cotton. The ballistic panel may be permanently sewn into the carrier or may be removable [23]. Although the overall finished product looks relatively simple in construction, the ballistic panel can be very complex. Even the manner in which the ballistic panels are assembled into a single unit can differ from one product to another. In some cases, the multiple layers are bias stitched around the entire edge of the panel; in others, the layers are tack stitched together at several locations. Some manufacturers assemble the fabrics with a number of rows of vertical or horizontal stitching; some may even quilt the entire ballistic panel. No evidence exists that stitching impairs the ballistic-resistant

properties of a panel. Instead, stitching tends to improve the overall performance, especially in cases of blunt trauma, depending upon the type of fabric used.

Plain woven fabric is more suitable for body armors. Neoprene coating or resination is also commonly used [18]. Needle-punched nonwoven fabrics are also used for ballistic protection. These are typically made from high-performance polyolefin fibers such as Dyneema polyethylene. The benefits of using nonwoven structures for these applications stem from their ability to provide protection against sharp fragments by absorbing projectile energy by deformation rather than fiber breakage as is the case with woven fabrics. When needle-punched nonwovens are used for ballistic protection, the felt structure should have very low mass per unit area. However, as the mass increases, woven structures become more superior to nonwoven felts [18]. Nonwoven felts should also be designed in such a way that a high degree of entanglement of long staple fibers is achieved at a minimum degree of needling since excessive needling can produce too much fiber alignment through the structure, which aids the projectile penetration.

In situations where high levels of protection (e.g., rifle fire) are required, body armor of either semirigid or rigid construction should be used. These are typically multilayer fibrous systems incorporating hard materials such as ceramics and metals. The heavy weight and high bulkiness of these body armors prevent their use in routine applications (e.g., by uniformed patrol officers or normal military operations) and restrict their use to tactical situations where it is worn externally for short periods of time when confronted with higher-level threats.

The development of more effective body armors is unlikely to cease as a result of the continuing development of weapons of increasing powers. As indicated earlier, the key aspect of development is the fibrous component from which body armors are made. The newest addition to the Kevlar line is Kevlar Protera, which DuPont made available in 1996. This is believed to be a high-performance fabric that allows lighter weight, more flexibility, and greater ballistic protection in a vest design due to the molecular structure of the fiber. Another development is the spectra fiber, manufactured by the former AlliedSignal, which is an ultrahigh-strength polyethylene fiber used to make Spectra Shield composite. This basically consists of two unidirectional layers of spectra fiber, arranged to cross each other at 0- and 90-degree angles and held in place by a flexible resin. Both the fiber and resin layers are sealed between two thin sheets of polyethylene film, which is similar in appearance to plastic food wrap. According to AlliedSignal, the resulting nonwoven fabric is incredibly strong and lightweight and has excellent ballistic protection capabilities. Spectra Shield is made in a variety of styles for use in both concealable and hard armor applications. Another product, also developed by the former AlliedSignal, uses the Shield Technology process to manufacture a shield composite called Gold Shield. This is made from aramid fibers instead of the Spectra fiber. Gold Shield is typically made in three types: Gold Shield LCR and GoldFlex, which are used in concealable body armor, and Gold Shield PCR, which is used in the manufacture of hard armor, such as plates and helmets.

Akzo Nobel has also developed various forms of its aramid fiber Twaron for body armor. This fiber uses more than 1000 fine spun single filaments that act as an energy

sponge, absorbing a bullet's impact and quickly dissipating its energy through engaged and adjacent fibers. The use of many filaments is believed to disperse an impact more quickly and allow maximum energy absorption at minimum weights while enhancing comfort and flexibility.

16.3.3 Protection against flame

Fire-related hazards include [21, 25, 26] flames (convective heat), contact heat, radiant heat, sparks and drops of molten metal, and hot gases and vapors. A self-sustaining flame requires a fuel source and a means of gasifying the fuel, after which it must be mixed with oxygen and heat [18]. Flame-resistant fibrous products should be developed to minimize the effects of these hazards in a very wide range of applications including firefighting, military operations, offshore oil and gas rig operations, law-enforcement rescue operations, aircraft and car crashes, and in many other situations where there is potential fuel spills and fire generation.

In general, flame resistance is the characteristic of a fabric that causes it not to burn in air. This can be achieved using fibers that are inherently or made to be flame resistant or using fibers treated with flame-retardant chemical substances. Typical flame-resistant attributes measured on fabrics (ASTM D6413) are char length (or the length of fabric destroyed by the flame so that it will readily tear by application of a standard weight), duration (seconds) of visible flame remaining on the fabric after the ignition source has been removed, and duration (seconds) of visible glow remaining on the fabric after all flaming has ceased. Passing the vertical flammability requirements is an essential criterion for protective clothing fabrics.

The key to developing efficient and effective flame-resistant fibrous products is to understand the elements constituting flammability. These include [22, 23, 25, 26] the following:

- Ease of ignition
- Rate of burning and heat release rate
- Explosion contents (e.g., coal, dust, and methane)
- Heat flux intensity levels (kW/m^2) and the way it varies during exposure
- Duration of exposure, including the time it takes for the temperature of the garment to fall below that that causes injury after the source is removed

It is also important to realize the factors associated with fibrous products that can assist in minimizing the effects of the aforementioned elements. These include as follows:

- The thermal and burning behavior of fibers (e.g., melting and shrinkage characteristics)
- The influence of fabric structure and garment shape on the burning behavior
- Properties of flame-retardant treatments (i.e., nontoxicity and the extent of smoke associated with flame-retardant additives or finishes)
- Properties of the protective garment (i.e., nature of usage and comfort aspects)
- The extent of insulation between source and skin, including outerwear, underwear, and the air gaps between them and the skin
- The extent of degradation of the garment materials during exposure and the subsequent rearrangement of the clothing/air insulation

– Condensation on the skin of any vapor or pyrolysis products released as the temperature of the fabric rises

The process of fiber combustion is a complex one as a result of the multiplicity of factors involved and their superimposed effects. This process typically involves heating, decomposition leading to gasification (fuel generation), ignition, and flame propagation [18, 25, 26]. The key performance characteristics expected from flame-resistant fibrous products are low propensity for ignition from a flaming source, slowing fire propagation, and generating low heat output (see Fig. 16.13). These criteria stem primarily from the fiber type used or the flame-retardant treatment applied. The role of the fabric or the garment assembly is also critical as they should act as a barrier against body skin burning by providing additional features including high thermal insulation and high dimensional stability (i.e., they should neither shrink nor melt). However, without an appropriate fiber type or a good flame-retardant treatment, these features will be impossible to meet. Accordingly, any development of flame-resistant fibrous product should primarily focus on fiber type, fiber characteristics, and flame-retardant treatments.

Unlike natural fiber, which tends to burn upon exposure to flame, synthetic fibers undergo noticeable physical and chemical changes under heat. In principle, thermoplastic fibers subjected to heat undergo two phases of changes: physical changes at their glass-transition temperature and melting temperature and chemical

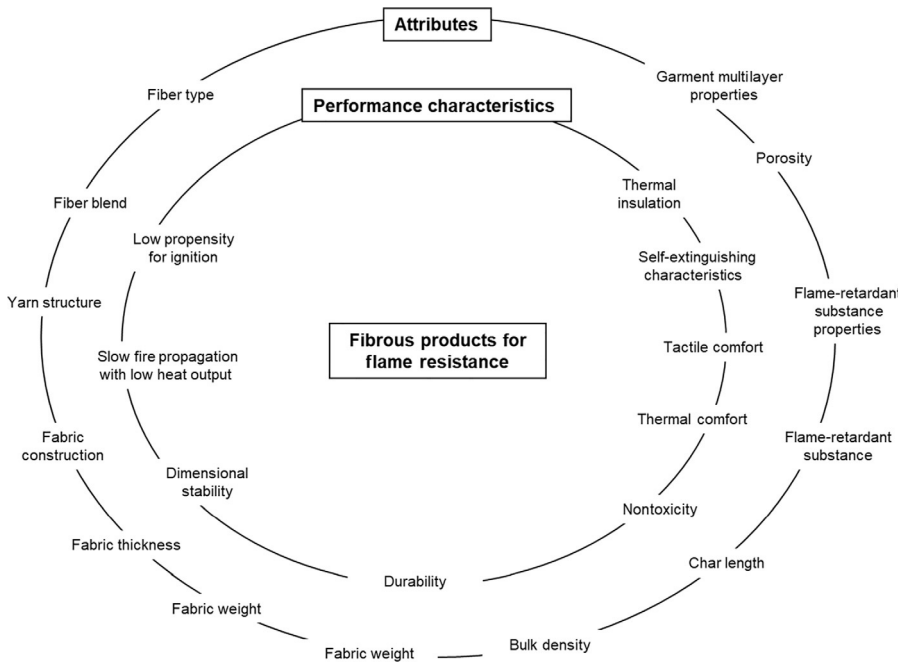


Fig. 16.13 Performance characteristics and related attributes of fibrous products used for flame resistance.

Table 16.5 Typical values of melting, pyrolysis, and combustion temperatures of some fibers [18, 25, 26].

Fiber	Melting temp (T_m, °C)	Pyrolysis temp (T_p, °C)	Combustion temp (T_c, °C)
Nylon 6,6	265	420–477	530
Polyester	255		480
Polypropylene	165	469	550
Kevlar	560	590	>550
Nomex	375	310	500
Oxidized acrylic		>640	
PBI		>500	>500
Cotton		350	350
Wool		245	600
Viscose		350	420

changes at their pyrolysis temperature, where thermal degradation occurs. Upon pyrolysis, volatile liquids and gases, which are combustible, act as the fuels for further combustion. After pyrolysis, if the temperature is equal to or greater than combustion temperature, flammable volatile liquids burn in the presence of oxygen to give products such as carbon dioxide and water [25, 26]. Table 16.5 lists some typical values of melting, pyrolysis, and combustion temperatures of some fibers.

Most thermoplastic fibers (e.g., nylon, polyester, and polypropylene) tend to shrink away from flame creating a self-contained spots. This feature is critical in minimizing the propensity for ignition and in slowing flame propagation. However, when these fibers are worn in the form of garments, concerns should be focused on skin burning upon melting of these fibers. Accordingly, conventional thermoplastic fibers fail to meet flame-resistant criteria. Instead, high-performance fibers such as aramid fiber (e.g., Nomex, DuPont), flame-retardant treated fibers (e.g., cotton or wool), and partially oxidized acrylic (Panox) fibers and polybenzimidazole (PBI) fibers are used for flame-resistant applications. Despite their high performance, these fibers should be tested in the garment form in view of the flame-related factors listed earlier and the particular application in hand. For example, it was found that the aramid fibers, in spite of their high oxygen index and high thermal stability, are not suitable for preventing skin burns in molten metal splashes because of their high thermal conductivity.

In view of the earlier discussion, fiber type, fiber characteristics, and flame-retardant finish are the most critical factors in determining the performance of flame-resistant fabric. In addition, some fabric-related attributes can also play significant roles. These include fabric thickness, bulk density, and fabric integrity (construction). As indicated earlier, fabric thickness has a direct impact on thermal insulation. For flame-resistant applications, the greater the fabric thickness, the better thermal insulation of fabrics made from flame-retardant treated fibers (e.g., cotton and wool).

This is not the case with thermoplastic fibers, whereas the thicker thermoplastic fiber fabrics produce more severe burns [25, 26]. At a constant fabric thickness, low fabric density (lower fiber/air ratio) will result in higher thermal resistance. These effects are important, particularly when flame-retardant treated fibers such as cotton and wool are used.

With regard to fabric integrity, shrinkage or expansion in the plane of the fabric does not substantially change the thermal insulation of the fabric itself. However, the spacing between fabric and skin or between garment layers may alter, with a consequent change in overall insulation. For example, if the outer layer shrinks and pulls the garment onto the body, the total insulation is reduced, and the heat flow increases. In addition, the most serious failure of flame-resistant garment is hole formation. When the fabric remains intact, its heat flow properties do not change greatly even when the component fibers are degraded, because heat transfer is by conduction and radiation through air in the structure and by conduction through the fibers (which is relatively small). Only when fibers melt or coalesce as a result of displacing the air or when they bubble and form an insulating char are heat flow properties substantially altered [26].

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About the Author

Yehia E. Elmogahzy heads the Elmogahzy Learning Consultant Firm (https://www.el-publish-learn.com/), a consultancy business offering services in the textile and paper industry, and acts as Visiting Professor at Rowan University and Montclair State University, New Jersey. His consultant firm has performed engineering and cost optimization analyses in more than 40 textile companies in the last 5 years, including companies in United States, Vietnam, Bangladesh, Pakistan, and Egypt. He has held distinguished positions as Dean of Math, Science, and Technology at Ocean County College, New Jersey (2009–13), Professor of Polymer Engineering at Auburn University, Alabama (1986–2009), and Site Director at the National Textile Research Center (2007–09) and is a member of the American Society for Quality Control (ASQC).

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