# CHAPTER 1

# The Importance of Decision Support in Materials Selection

## 1.1 INTRODUCTION TO MATERIALS SELECTION

The selection of the most appropriate material for a particular purpose is a crucial function in the design and development of products. Materials influence product function, customer satisfaction, production systems, product life cycle, who is going to use or produce it, usability, product personality, operating environment, and costs in a complex way.

Materials selection either can be carried out to choose alternative materials for changes to the design of an existing product in order to reduce say cost or weight, meet new legal requirements, overcome failure occurrence, or satisfy different market demands, or it can be used to choose materials for the design of a completely new product. The materials selection process is similar for existing and new products although the starting point and information requirements may differ. The interdisciplinary effort required in most cases is nontrivial and the engineering designer not only requires detailed, accessible, and timely information about the properties of the materials but also knowledge of multi-criteria decision-making (MCDM).

This book describes the main principles and strategic application of MCDM techniques to support engineering designers compare the performance of established materials, new materials, and hybrid materials when selecting the most appropriate materials for product design.

## 1.2 BACKGROUND AND JUSTIFICATION FOR FORMALIZED MATERIALS SELECTION

There are an enormous number of materials available, each with a range of different properties and behaviors. New materials are also constantly being developed with enhanced properties, expanding the list of options available to the engineering designer. The material properties, and combination of properties in the form of performance indices, can be mapped on to materials' selection charts, pioneered by Ashby [1]. In the charts, the materials naturally cluster into different classes of metals, polymers, elastomers, glasses, and ceramics. However, only parts of the charts are populated with materials, leaving holes or gaps in the selection space. New materials with enhanced properties can reduce the size or fill gaps within clusters, or expand the boundary of clusters, or the gaps between clusters can potentially be filled or "bridged" with hybrid or multimaterials such as composite materials, as shown schematically in Figure 1.1.

The historical evolution in the use and development of materials reflects the progress of the interdisciplinary science from early civilizations until today [2]. The strategy with respect to materials usage started with the Stone Age (greater than 10,000 BC) by using the available materials such as stone and wood and then later copper and bronze (Bronze Age, 4,000 BC to 10,000 BC), and iron (Iron Age, 1,000 BC to AD 1620 ). Afterward, the strategy gradually focused on the optimization of specific classes of materials. This led to the development of tools for comparing and selecting materials from different classes of materials already optimized in terms of their engineering potential. Today can be followed by (2013), the emphasis has shifted more toward the consideration of economical aspects and environmental impact. This has created a tendency toward the development of materials using design strategies with an increased importance of modeling and multifunctionality of materials [2]. However, there is still

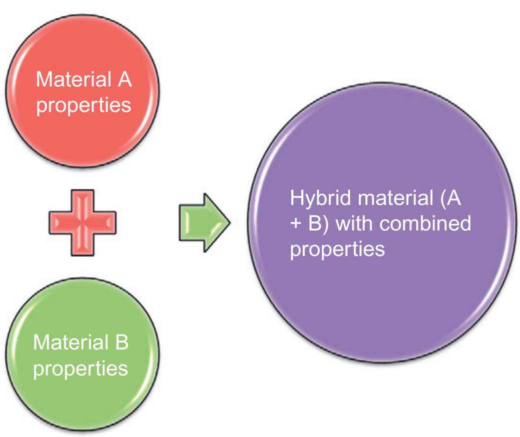


*Figure 1.1 Hybrid materials combine the properties of two (or more) monolithic materials.*

a lot of fundamental materials research being conducted without careful consideration being given to its practical application [3]. This not only justifies the need for the greater use of materials selection tools, but also the importance of supporting decision-making to better understand and manage the multiobjective product design process.

## 1.3 DECISION-MAKING AND CONCESSION IN PRODUCT DESIGN

Introducing a completely new product or improving an existing product involves a complex chain of interdependent activities including design, analysis, materials selection, and consideration of manufacturing processes, and all depend on MCDM. Besides influencing material properties, process selection is a prerequisite to manufacturing equipment selection. However, materials selection used to be only a minor part of the design process [4] and has therefore not received the same level of research and development as other fields of design. The selection of suitable materials for a specific purpose is a difficult, time-consuming, and expensive process because of the large number of available materials with complex relationships and various selection parameters. As a consequence, approximations are made with materials frequently being chosen by "trial and error" or simply on the basis of what has been successfully used in the past. This approach can lead to compromise and unpredictable outcomes, possible premature failures, and limits the ability to achieve an optimal choice of materials.

The stage reached in the design process is important because the nearer a product is to manufacture level, the greater is the cost of making any design change [5]. It has been estimated that the relative cost of a design change after manufacture is 10,000 times more than at the conceptual stage of design [5]. Therefore, it is worth making decisions carefully and spending enough time early on in the design process using systematic selection techniques. This makes it easier to manage the "trade-offs" between design, materials, shape, and manufacturing processes and lead to an optimum design solution.

To satisfy customer requirements, manufacturing organizations must be continually aware of product costs, reliability, durability, recyclability, and market trends. These attributes should be addressed strategically by manufacturers through a continuous process of improvement in an ongoing effort to improve their products [6]. This will only be fully achieved through optimum decision-making about design, materials, and manufacturing processes [7,8] and provides the opportunity for sustainable and profitable growth. To support this process, MCDM techniques have developed dramatically in both theory and practice, especially in the fields of design and manufacturing, with growing interest in their application to materials selection.

## 1.4 THE POSITION OF MATERIALS SELECTION IN THE ENGINEERING DESIGN PROCESS—FROM CONCEPT TO DETAIL STAGES

The successful design of an engineering component is integral to satisfying the functional and customer specified requirements for the overall product it forms a part, utilizing material properties, and capabilities of suitable manufacturing processes [9]. The behavior of a material used to create a component will be affected by component geometry, external forces, properties of stock material before processing, and the effect of manufacturing (or fabrication) method [10]. The evaluation of the typically large number of design solutions (altering the size, shape, and mass of the component) and suitability of an even larger number of different materials rapidly becomes too complicated to be intuitive. This highlights the value of being able to use MCDM to support decision-making in the engineering design process. Although experimental-based selection of a material, for example, testing and prototyping, for a specific design solution is the most accurate; it quickly becomes unreasonable due to the time required and the high costs of experiments, especially if several materials have to be considered. Alternatively, other more viable options can be considered such as computer-based simulations, but the ranking of materials should have already been successfully completed during the initial stage of the design process [6].

Figure 1.2 shows the connection of materials selection and continuous improvement in product development. There is the option to develop a new material but this adds cost and risk to the design efforts and has been highlighted here for the occasion when there is no acceptable material options [11,12]. However, the added cost and risk may be worthwhile if there is an innovation that provides a product with a competitive advantage compared to products produced by other companies. In Figure 1.3, quality tools such as quality function deployment (QFD) [13,14] helps marketing and design teams incorporate the voice of the customer in product designs, increasing the likelihood that the final product will successfully satisfy the customer's needs. Failure modes and effects analysis (FMEA) [15] will indicate the material's attributes that must be investigated, controlled, and monitored to ensure the reliability of the component in which the material is used. It will also indicate the manufacturing process steps and controls that are required to make a product, subassembly, or component that will consistently meet its design requirements. Therefore, QFD and FMEA, used as quality tools in design, can dramatically improve product development efficiency because it leads to systematic design, materials selection, and manufacture.

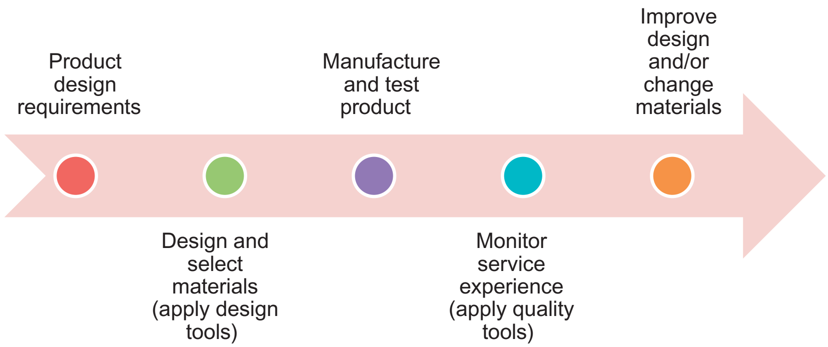


*Figure 1.2 Materials selection and continuous improvement in product development.*

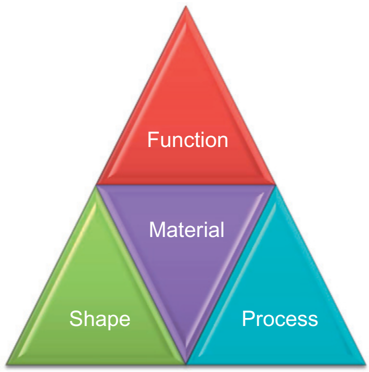


*Figure 1.3 The interaction between material, function, shape, and process.*

Ashby [16] and Ashby et al. [17] map the application of design tools and materials selection on the traditional systematic product development process. The resulting methodology is a "design-led" approach to materials selection. Design tools, of which there are many, and computer-based, enable visualization (e.g., 2D computer-aided design), modeling (e.g., 3D solid modeling) and analysis (e.g., finite element analysis) to be conducted, as well as interactive simulation of evolving design solutions. To ensure that product design, materials, and process selection are done together, design for manufacture (DFM) and rapid prototyping tools are also regularly used. There are fewer tools available that are dedicated to materials selection, and even less for materials process selection, although many design tools make use of materials properties databases. At each stage, from concept to detail design, information about the materials gradually changes in the level of detail and precision, as the number of available materials reduces from initially all possible materials to finally one material.

Fundamentally, the strategy for selecting materials is determined by the need to satisfy design requirements and involves five main stages:

1. Definition of the design [4].
2. Analyzing and translating the design requirements (expressed as constraints and objectives) into material performance indices/properties [4,18–20].
3. Comparing the properties required with a materials property database in order to select a few candidate materials that look promising for the application [4,18–23]. Screening is based on the idea of classifying performance requirements into "rigid" and "soft" requirements [24]. "Rigid" requirements can be used for the initial selection of materials to eliminate any unsuitable groups. For instance, metallic materials are eliminated when selecting materials for an electrical insulator. Soft requirements are normally subjected to negotiation and compromise and therefore involve more complicated decision-making. Examples of requirements in this group consist of mechanical properties, physical properties, and cost, which are normally compared on the basis of their relative importance to an engineering design. For instance, high specific stiffness and strength materials such as polymer composites are used for advanced sports equipment.

4. Developing, comparing, and ranking alternatives [18,20–22], and using "soft" material requirements to further narrow the field of possible candidates down to a few promising materials.
5. Searching for supporting information about the top-ranked candidate materials [18], evaluation and decision for the optimal solution [4,19,20,22], and finally verification tests [4].

## 1.5 UNDERSTANDING THE FUNCTIONAL REQUIREMENTS AND DESIGN CRITERIA IN SELECTING MATERIALS

The performance requirements of materials can be classified into two main categories: "rigid" or "go-no-go" requirements and "soft" or relative requirements [24]. Rigid requirements should be met by the material if it is to be considered at all. Such requirements can be used for the initial selection of materials to eliminate unsuitable classes of materials. For instance, metallic materials are eliminated when selecting materials for an electrical insulator. "Soft," or relative, requirements are subject to negotiation and trade-offs.

Apart from materials' properties, other requirements, such as those on materials processing during component manufacturing and those on in-service conditions relating to the materials of components, should also be taken into account in materials selection [25].

The design of a product is either cost driven or performance driven, and the approach taken makes a significant difference when choosing materials. An example of a cost-driven product is a mass produced motorcar or drinks bottle, and an example of a performance-driven product is a bespoke biomedical prosthesis or a tennis racquet. The selection of cheaper materials may lead to reduced manufacturing organization cost, but the selection of lighter materials although more expensive, in say a motorcar or aircraft, may reduce fuel consumption, service cost, and environmental pollution.

## 1.6 THE RELATIONSHIP BETWEEN MATERIALS SELECTION AND PROCESSING

The selection of a material must be closely coupled with the selection of a manufacturing process. Manufacturers are always on the lookout for new materials and improved processes to produce better products, and thus maintain their competitive edge and increase their profit margin [26].

Recent developments in manufacturing techniques are facilitating the development of new materials and improving the properties of current materials for different engineering applications. Consequently, the number of materials and new manufacturing processes is constantly on the rise with two main objectives: low cost and high performance [27]. Any change in a material will likely cause a change in the manufacturing process, geometry, shape, and performance (Figure 1.3). Often there are many ways of creating components (shaping, joining, finishing, etc.) but choosing the optimum route is difficult [25]. With the increasing level of sophistication in both materials and processing, it is insufficient to just rely on experience alone [28]. The large number of materials and the growing number of processes and subprocesses available to engineering designers, coupled with the complex relationships between different selection parameters, often make the selection of materials for a given component a difficult task especially when there are cost limitations.

Ashby [16] extended his concepts of materials selection charts for properties at the conceptual design stage to the development of process selection chart. A lot of attention has been directed in recent years toward developing design methodologies for manufacturing and assembly for enhancing manufacturability and integrating material and process concepts through proper design with the aim of cost reduction, enhancing the product quality, and delivery.

The production of tailored materials requires the development of new processing routes or important changes to conventional routes [2]. This subject is strongly important with regard to new tendency for multifunctional materials, modeling, and computational materials engineering. The goal is to select a material and process that maximizes the quality and minimizes the cost of product. The design and manufacturing process, except for the most simplest of products, is very complicated and involves making thousands of decisions in which any mistake can lead to unnecessary activities, extra cost, and customer dissatisfaction. Therefore, achieving optimum decision-making in the integrated chain of actions for developing new, or improving existing, products is essential [6]. Figure 1.4 shows the stages of material selection and its integration with process selection [18].

Recently, the following sequence of tools was proposed to facilitate selection processes as an integrated material and process selection framework [29]:

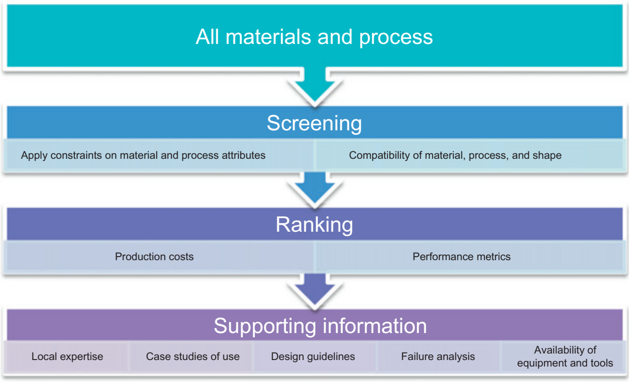


*Figure 1.4 The different stages for materials and process selection in design.*

1. Documentation management that allows ideas to be translated into engineering design.
2. Matrices that relate incompatibility between materials and manufacturing processes.
3. Matrices that relate typical properties to specific requirements.
4. Models of manufacturing processes that take into account limitations in the geometry of components.
5. Multi-criteria analysis techniques.
6. Screening preselection techniques.

## 1.7 THE SIGNIFICANCE OF DESIGN ADAPTATION AND MATERIALS SUBSTITUTION

There are many traditional materials that have served in engineering applications for a long time that are now being replaced by the so-called "new materials" in order to meet the demands of cost reduction and performance enhancement. If a decision is taken to substitute a new material for an established one, care must be taken to ensure that all the characteristics of the new material are well understood because a large number of product failures have resulted from new materials being used before their long-term properties were fully known [26]. The introduction of new, or modified, or alternative materials and processes for a given application is dependent on satisfying a lot of different factors [30]. The common reasons for materials substitution include [30]:

- Taking advantage of new materials or processes
- Improving service performance, including longer life and higher reliability

- Meeting new legal requirements
- Reducing cost and making the product more competitive
- Environmental constraints.

With the large range of properties that describe any material, it would be very rare to find a material that has the absolute ideal values for a function, therefore either a "trade-off" of properties to select the best option from available materials or tailoring a multifunctional material based on the requirements is usually required. Both approaches need MCDM to deal with conflicting objectives design to obtain optimum performance.

## 1.8 MATERIALS SELECTION AND SUSTAINABLE PRODUCTS

The main aim of "green" design, ecodesign, design for environment, and sustainable design is to manufacture products in a way that reduces the use of nonrenewable resources, uses less energy, does not directly or indirectly pollute the environment, and can be reused or recycled at the end of their useful life [31]. The evaluation of product sustainability should consider the raw materials production, the fabrication process, energy consumption, transportation, and recycling. Therefore, one of the major opportunities for practicing sustainability is material selection due to its potential impact on natural environmental systems. In particular, a sustainable material selection means selecting materials that minimize environmental degradation over the whole life cycle of the material, from initial acquisition to eventual disposal or recycling [32]. Some examples of sustainable design of products influenced by materials occurring at the different stages of the product life cycle include the use of low toxic emission aqueous-based paint systems replacing solvent-based paint systems for motorcar bodies at the product manufacturing stage, the use of low energy consuming fluorescent lightbulbs replacing incandescent lightbulbs at the product use stage, and the use of recyclable or biodegradable beverage containers for the product disposal stage.

The processing of materials has significant impacts on the environment, including the use of water, land use patterns, undesirable emissions to air, water, and land, and the consumption of other important environmental resources [33]. Therefore, materials selection in the product design process must be carried out carefully to achieve sustainable products. In this regard, life cycle engineering (LCE) is one of the best methods. However, because of the large variety of materials and processes, considering LCE when selecting materials may require handling a large amount of data and performing many calculations [32]. Hence, it is reasonable to perform LCE after first obtaining a short list of candidate materials.

The following are some common design principles that help reduce environmental impact of materials [31,33]:

- Use low-impact materials by choosing nontoxic materials or recycled materials that require little energy to process.
- Use manufacturing processes that require less energy.
- Make longer-lasting and better-functioning products that will have to be replaced less frequently.
- Design products for reuse and recycling.
- Design products with less material.
- Use materials that come from nearby (locally sourced).

There are more details about materials selection and the design and development of sustainable products in Ref. [34].

## 1.9 QUALITATIVE VERSUS QUANTITATIVE APPROACHES TO MATERIALS SELECTION

A materials selection strategy has three main components [18]:

1. The formulation of constraints that must be satisfied if the material is to fill the desired function.
2. The formulation of a performance metric or value function to measure how well a material matches a set of requirements.
3. The use of a search procedure for exploring the solution-space to identify materials that meet the constraints, then rank the materials by their ability to meet the requirements.

A structured set of guidelines to help select an optimal choice of materials when designing engineering products were developed by Edwards [35]. This is particularly beneficial for novice engineering designers but also serves as a checklist for more experienced engineering designers.

For materials selection in which there are numerous different choices and many various criteria influencing the selection, it is difficult for engineering designers to evaluate qualitatively, current and new materials for a particular application, therefore an accurate approach is required [36]. The conversion of qualitative information into quantitative information allows quantitative approaches to be used and provide the basis for direct comparisons to be made between each type of information. This approach is particularly useful at the conceptual design stage when information about materials is vague but becomes more problematic to apply further along the design process as the information about materials becomes more precise.

## 1.10 THE ROLE OF COMPUTER-BASED MATERIALS SELECTION AND MATERIALS DATABASES

The available set of materials are rapidly growing both in type and in number [37]. An engineering designer can only be expected to know a small part of the ever-growing body of knowledge on materials. Despite much of the materials information being available in standards, handbooks, and journal papers, actually finding this information is difficult and time-consuming and many potential materials might be overlooked. At one time, an engineering designer could rely on a handbook and personal experience to select the most appropriate materials for an application. Nowadays, engineering designers are at risk of seeing their knowledge on materials easily go out of date, so are forced to look for systematic techniques for managing and analyzing engineering data on the growing array of materials [37,38].

Fortunately, modern computer-based design tools, of which there are now many, support different aspects of the design decision-making process, but gaps still exist [25]. A recent study has identified about 300 different software packages, databases, and web site sources of information on materials [38]. This not only demonstrates the increasing number of materials' promoters and users but also the shortcomings of current systems for selecting materials. The current systems are either configured to provide decision support or information based but their integration has been limited. Therefore, systems that mostly provide decision support leave the burden of considering the large number of alternatives on the decision-maker (the engineering designer in this case). Database systems (the majority of electronic sources of information on materials) contain a lot of data and information but despite some using "search engines" and easy to use interfaces, provide limited decision-making support when the number of criteria increase. The combination of decision theory and database technology has the potential to greatly improve the overall effectiveness of the materials selection process and therefore lead to better product design [39].

The following chapters describe the principal developments in the use of MCDM techniques for selecting materials in the design of products.

## REVIEW QUESTIONS

1. Discuss the materials information needs at each stage of the design process and its effect on decision-making.
2. Why is it necessary to be as thorough as possible and consider a large number of different materials in the early design stage?
3. Why are the consequences of making compromises in materials selection when designing a product?
4. What is the difference between material attribute identification and materials selection?
5. Why is it important to take into account manufacturing processes when selecting materials?
6. Discuss the issues involved when deciding to use a newly-developed material in a product.
7. Discuss the differences between cost- and performance-driven product designs with respect to materials utilization.
8. Why is it essential to assess the consequences of any change in properties and the design of the whole product when substituting materials?
9. Discuss the influence of materials in the sustainable design of products occurring at the different stages of the product life cycle.
10. What are the advantages of using hybrid materials and why can sustainable design adversely affect their use?
11. Discuss the problems associated with incorporating qualitative information in a formalized materials selection process.
12. Why is it helpful to integrate design tools for facilitating improved decision-making when selecting materials?

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