CHAPTER 12

MAKE IT REAL

Finding the Most Suitable Materials and Components

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Learning Objectives

So that you can advise your student design teams on what information sources are available to help them turn their design concepts into reality, upon reading this chapter you should be able to

• Describe and illustrate the major challenges student design teams face in finding and then deciding between the multitudinous options available when they have to select materials and components
• List the major factors that should be considered when selecting a material for fabrication or commercial off-the-shelf components or systems
• Demonstrate effective and efficient strategies for selecting the most appropriate materials to use in fabricating a new product
INTRODUCTION

The previous stages of the design process have helped determine what the students’ artifact needs to do, how well it needs to do it, and possible ways to accomplish this. Once a preferred concept to solve the design problem has been selected, the details of how to actually build the artifact must be determined and embodied in the final artifact.

Selecting the most appropriate and cost-effective materials and components is critical to the success of a design project (Ashby, 2011a). Without careful materials selection, the resulting artifact may be suboptimal in terms of performance, ease of manufacture, fabrication, or cost (Jahan & Edwards, 2013). A disciplined and methodical investigation of alternative ways to realize the concept is necessary in order to create competitive, cost-efficient design solutions. Embodying a design concept includes considerations of both the materials used and how these materials will be shaped or otherwise transformed into the manufactured artifact. For example, if a particular type of metal is too brittle to be extruded in a manufacturing process, even if it has the appropriate mechanical properties, it may not be appropriate for use in the final project.

This chapter describes a general process for materials selection and a discussion of strategies and resources for locating materials. When searching for information, students need to determine the most important sources for finding material properties and assess the reliability of those sources. In many cases embodiment of a concept is achieved in part through the selection of existing commercial off-the-shelf components (COTS); therefore, consideration is also given to finding information on the performance and other specifications of COTS.

COMMON CHALLENGES FOR STUDENTS

Students can be overwhelmed by the vast number and variety of materials available to them. Whether it is the hundreds of different kinds of steel available on the market, or the multitude of chipsets produced by dozens of manufacturers, students struggle to locate materials or components relevant to their need. They often take the first material that looks reasonable, perhaps the first item that shows up on an Internet search, rather than trying to systematically find the best material for the job.

Materials specifications and data sheets often contain large amounts of difficult to understand technical detail, and consequently, students have considerable difficulty in sorting through and interpreting the voluminous data they do find, or knowing how to distill or translate this into usable design information. This is made all the more difficult if the student does not have a thorough grasp of fundamental concepts in material properties and how these relate to material behavior (e.g., Young's modulus, conductivity, flexibility, or rigidity). An artifact being designed typically has multiple components. The materials for each component must be carefully selected so that the assembly performs properly in the final product.

For example, a swimming pool diving board has limitations on size, load capacity, and deflection when in use. Further, it must resist the dynamic loads that a diver applies to it in performing a series of dives. Its ability to store strain energy like a spring is a critical parameter. Indeed, this is perhaps the most important function that a diver values in the board’s design, as it translates into the ability to spring high into the air when beginning the act of diving. The diving board must provide this rebound energy
Refine Solution with minimal deformation and without excessive vibration. So it must be a finely tuned cantilever beam, light and stiff on the one hand, yet able to quickly damp out vibration after the dive is complete (Chopra, 2012).

**MATERIAL SELECTION STRATEGY**

In order for students to be able to search effectively, they first need to know what it is they are looking for. Often they haven’t sufficiently determined the precise problem they are trying to solve (e.g., the performance requirements their component needs to meet), and without clearly understanding the problem, students have difficulty recognizing a viable solution.

The following question-based strategy for material selection and COTS component selection can be used by students to overcome many of the difficulties they often experience when embodying their design concepts.

1. What performance is required from the component?
2. What are the environmental factors across the life cycle of the artifact?
3. Are there commercially available components or products that will do the task?
4. What relevant information is needed to be able to select a suitable material?
5. What materials are potential candidates for this application?
6. Are there newer materials or technologies that might offer innovative design solutions?
7. What material selections charts or software are available?
8. What form and size do the materials come in?
9. How will the materials be processed or shaped in order to make the component?
10. Are there other constraints related to the materials that must be satisfied?

Various classes of materials are available, and each class contains many different types of materials (see Table 12.1).

Through the use of a variety of materials based on properties, applications, cost, and

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**REALITY CHECK 12.1**

**Role of Materials in Successful Engineering Design**

Materials play a critical role in successful engineering design. Proper material selection can sometimes decide whether or not a system is designed so that it is safe to the users and the public. In December 2012 a shark tank in a Shanghai shopping center collapsed just two years after it was constructed, injuring 16 people and killing the sharks and dozens of other sea animals it housed. Investigators concluded that two years of UV light exposure from the sun and thermal cycling from the outdoor climate had caused the 10-inch-thick acrylic glass panel to become brittle enough to crack (Ho, 2012).

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**REALITY CHECK 12.2**

**Designing a Green Roof**

A lightweight vegetated roof research team was challenged with finding a material for their substrate medium. In addition to common properties desirable in similar applications, environmental impacts such as resource extraction, total embodied energy in production and distribution, and disposal were most important to them. They first made a list of possible material choices based on bulk density, durability, and absorptivity, then each material was put through a life cycle analysis, which revealed information about sourcing and the process required for manufacturing. For example, EPS (Expanded Polystyrene) had excellent properties that would work well for their system; however, due to its large embodied energy and the fact that it is not biodegradable, it had to be eliminated as a candidate.
Refine Solution

### Environmental Considerations

In the diving board example from the previous section, because the board must operate in a very moist environment, if wood is used in this application it has to be resistant to damage when constantly wet or exposed to wet/dry cycles. This often requires sealants on the wood to keep it dry. It also requires that the hardware used to mount the board on a diving platform must resist any form of corrosion. Galvanized steel was the normal standard in wet environments. Similar design constraints were set on boats made of wood. Steel fasteners were usually galvanized (coated with zinc) to resist corrosion (Dowling, 2007).

In contemporary diving board design, wood has been replaced by fiberglass. Glass fibers in epoxy are much lighter and stronger than wood and can be formed into the specific shapes most efficient in providing the desired performance characteristics. These new composite materials can be optimized as to strength, stiffness, ability to store more energy, and even improved damping characteristics. There is very little water penetration and therefore no need for sealants, although some are painted and coated with a gel coat of epoxy resin, giving them a very smooth and attractive appearance. Fiberglass, unlike carbon fiber reinforced resin, is not terribly expensive and is therefore broadly used in marine applications (Masuelli, 2013).

### Commercial Off-the-Shelf (COTS) Components

When selecting materials, it is also necessary to determine whether any COTS components should be used in the product design. While many engineering students think first of designing their own custom solution to a problem, down to the individual parts, custom designed components may be prohibitively expensive to produce in quantity with marginal increase in efficiency and performance of the final product.

The market provides access to a variety of available COTS. In the overall design process, these components can play an important role in the successful design project. According to Farr (2011), “A commercial off-the-shelf (COTS) component is an item bought from a third party supplier and integrated into a larger system” (p. 207). Some examples of COTS

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**Table 12.1: Classes and Examples of Materials**

<table>
<thead>
<tr>
<th>Class</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals and alloys</td>
<td>Iron, steel, copper and alloys, aluminum and alloys, nickel and alloys</td>
</tr>
<tr>
<td>Polymers</td>
<td>Polyethylene (PE), polymethacrylate (acrylic and PMMA), nylon or polyamide (PA), polystyrene (PS), polylactic acid (PLA)</td>
</tr>
<tr>
<td>Ceramics and glasses</td>
<td>Alumina (Al₂O₃, emery, sapphire), magnesia (MgO), silica (SiO₂) glasses and silicates, silicon carbide (SiC)</td>
</tr>
<tr>
<td>Composites</td>
<td>Fiberglass (GFRP), carbon-fiber reinforced polymers (CFRP), filled polymers</td>
</tr>
<tr>
<td>Natural materials</td>
<td>Wood, leather, cotton/wool/silk, bone, rock/stone/chalk</td>
</tr>
</tbody>
</table>

Data from Ashby & Jones, 2012.
components include computer software, hardware, and construction materials.

By using COTS components, it is possible to create a cost-effective prototype of a particular design project. For example, Winchenbach and Segee (2011) point out that by acquiring and assembling COTS from the market, it is possible to reduce significant time and cost in designing a mobile robotic platform. The use of COTS to improve cataloging of Inner Earth Object (IEO) items was implemented by the German Aerospace Center in its AsteroidFinder mission. This approach allowed the development of an efficient and robust system design solution within the limitations of a smaller satellite project (Findlay et al., 2011). Several leading aerospace companies have started using new solutions employing COTS tool providers and in the process have discovered that these methods were the best fit for the individual needs of product developers (Low, 2011).

It is important for students to search for what COTS components are available that they can use in their design solution. While significant reduction in cost is possible by using a COTS approach, there are other issues such as reliability and quality that need to be considered. While searching for such components, focus on these issues is critically important in designing a product which is both reliable and cost-effective.

**PROCEDURE OF MATERIAL SELECTION**

Properly selecting materials is a critical step in determining the best solution for a design application. It must be noted that the process is typically not linear, since there are separate design requirements that depend on specified design criteria; it is not just the physical properties that determine the best material. For example, the budget will be set by the client, and the client may want the product to look a certain way for marketing purposes. These considerations must be taken into account throughout the selection process.

The first step is to determine the physical constraints on the design item, such as size, loads, and durability (see Box 12.1). Once these constraints have been determined, they are used as inputs that are plugged into functions to determine the material physical properties required, such as density, strength, and stiffness. This is an important step that can immediately eliminate many possible materials due to inappropriate performance characteristics that simply will not do the job. Material selection charts are very useful in isolating the range of materials that have the correct prescribed property profiles (Ashby, 2005). For example, the CES Selector software offered through Granta Design (http://www.grantadesign.com) can generate various charts.

Realities check 12.3
Commercial Off-the-Shelf Components

Companies such as Adafruit Industries (www.adafruit.com), SparkFun Electronics (www.sparkfun.com), and Maker Shed (www.makershed.com) sell low cost COTS software and electronic parts, such as the Italian microprocessor Arduino. These materials are extremely useful for low cost prototyping. There are extensive professional and hobbyist communities that provide an abundance of freely available information and open source scripts that can perform various prototyping functions. Students at the Drexel Smart House in Philadelphia use the Arduino platform paired with various flow meters, sensors, and servos to control an indoor farming prototype. This allows them the ability to quickly change microprocessing controls, which gives them the flexibility to efficiently experiment with many different program settings of the automated system toward finding the most optimal system design at a low cost.
that are helpful in comparing various material properties desired for the specific design. If a very strong lightweight material is desired, strength-to-density and Young’s modulus-to-weight ratios are dominant material properties. If embodied energy and cost are also concerns, strength-to-relative-cost and strength-to-energy-content could be deciding factors. The charts provided by the CES Selector and other such software can be used during the material selection process to isolate the area identifying all possible materials that apply to the design solution (Ashby & Cebon, 2007). Examples of charts for a variety of materials, along with an in-depth explanation of the significance of each chart, are available at http://www.me.uprm.edu/vgoyal/inme4011/Online_inme4011/Topic2_MaterialSelection/AshbyCharts.pdf.

A list of materials that have the desired properties can be generated using material selection charts to eliminate materials that fall outside the various design constraints. Once the materials with the required physical properties have been located, candidate materials can be ranked using objectives specific to the application and desire of the client and designer, such as aesthetics, manufacturability, or environmental considerations. If a material does not look good, cannot be practically manufactured, or degrades over time because of environmental exposure, it will not be a good choice.

The final element in material selection is total cost. Material selection charts can be used to calculate the cost per unit mass, which can be fed into total cost estimates based on how much of the material is needed compared to that needed for alternative design solutions. This procedure allows the student to separate design constraints from desirable material properties before selecting the least cost material that will be best suited for the application. Students also may want to research the history of top-ranked candidates to see if there are pitfalls, or a track record of performance that may raise caveats or reinforce the choice of that material.

### BOX 12.1

**Steps in the Materials Selection Process**

1. Translate design requirements
2. Screen using constraints (i.e., eliminate materials that can’t do the job)
3. Rank using objectives: find materials that do job the best
4. Seek documentation: research the history of top-ranked candidates (see if there are pitfalls, or track record of performance of the materials)

Data from Ashby, 2012.

**LOCATING INFORMATION ABOUT MATERIAL PROPERTIES**

Mechanical properties of materials, such as fracture toughness, tensile strength, hardness, creep, and fatigue strength, are predictors of the way materials behave during the application of different types of stress (Stoloff, 2012). For example, suppose a design problem requires exploring mechanical properties of materials to understand how much deformation a material can withstand before breaking or how much resistance a material offers to fracture. In this case, ductility and toughness are two examples of mechanical properties which need to be explored. Other mechanical properties include elastic moduli, yield strength, tensile (ultimate) strength, compressive strength, fatigue endurance, and failure strength. While understanding these
properties is important, it is equally important to learn how to find material properties using a variety of information resources and tools currently available. These properties can be found in subject-based online handbooks, such as the *Engineer’s Handbook* (http://www.engineershandbook.com), and scientific reference works that libraries subscribe to such as Knovel and CRCNetBase. It is important that students become familiar with using these online resources, as the more they use them, the more likely they will be to use high-quality sources instead of more dubious open Web sources in their search for appropriate materials. In this case, being able to search through compiled data has no substitute in the open Web. It is also important for students to always check the library’s reference section for handbooks that will contain much of the same information found online.

**SELECTED SOURCES OF MATERIAL INFORMATION AND DATA**

There are a number of resources available that provide access to property data of different materials.

**ASM Materials Information Online**

The ASM Materials Information database (http://products.asminternational.org/matinfo/index.jsp) contains the contents of the ASM Handbook series, among other content produced by ASM. It contains peer-reviewed, trusted information in every area of materials specialization. This series is the industry’s best known and most comprehensive source of information on ferrous and nonferrous metals and materials technology.

**CES Selector**

CES Selector (http://www.grantadesign.com/products/ces) is a powerful software application that offers extensive materials property data, advanced graphical analysis, and specialized tools to support materials selection and substitution decisions. The CES Selector database allows students to create interactive charts as a function of different properties to assist in the selection of appropriate materials. It was developed for the education market, providing an intuitive graphical interface and hyperlinked definitions of properties throughout, to assist students in navigating the material information landscape.

**Knovel**

Knovel (http://www.knovel.com) provides electronic access to leading engineering reference handbooks, databases, and conference proceedings. It was the first publisher to extract data from handbooks, allowing the search for material properties across a wide variety of titles.

**The Materials Project**

The Materials Project (http://materialsproject.org) is an open science initiative that makes available a huge database of computed material properties. The Materials Project aims to reduce guesswork from materials design in a variety of applications, as experimental research can be targeted to the most promising compounds from computational datasets. Researchers will be able to data-mine scientific trends in material properties. By providing materials researchers with the information they need to design better, the Materials Project aims to accelerate innovation in materials research.
Matweb

MatWeb’s (http://www.matweb.com) searchable database of material properties includes data sheets of thermoplastic and thermoset polymers such as ABS, nylon, polycarbonate, polyester, polystyrene, and polypropylene; metals such as aluminum, cobalt, copper, lead, magnesium, nickel, steel, superalloys, titanium, and zinc alloys; ceramics; plus semiconductors, fibers, and other engineering materials.

NIST Data Gateway

The National Institute of Standards and Technology (NIST) Data Gateway (http://srdata.nist.gov/gateway/) provides easy access to many (currently over 80) of the NIST scientific and technical databases. These databases cover a broad range of substances and properties from many different scientific disciplines. The Gateway includes links to free online NIST data systems as well as to information in NIST PC databases available for purchase.

LOCATING COMMERCIAL OFF-THE-SHELF (COTS) COMPONENTS

There are many resources available online that can assist in sourcing the appropriate COTS equipment and manufacturers (see Box 12.2). Some suppliers focus on providing only specialized types of material such as software and electrical, mechanical, and construction materials. For example, a very common COTS item is a power supply. Many products require power in order to function, and it is more beneficial to the designer to choose a pre-manufactured power supply rather than to design and produce it from scratch. There are several caveats to be aware of using COTS, such as the possibility of a third-party component vendor’s going out of business or dropping the support of a certain product. When using a COTS component, it is important to view the spec sheets to determine what specifications and tolerances the component has been built to and to ensure as objective a comparison between components as possible. Consulting product review sites can also help when choosing between components to see whether a particular community believes the components are really performing up to their specifications.

SUMMARY

The embodiment of a design concept in order to make it a practical reality demands finding the right material or identifying the most appropriate components that can meet the product requirements. Selection is not a simple process. It must be undertaken in a disciplined and methodical way, using a coherent search strategy. It sometimes requires trial and error, experimentation, and analysis of results before the most cost-effective, environmentally sound
material selection process is complete. There are numerous online resources, handbooks, and selection software to aid in this process. However, these tools are only as good as the underlying strategy that the designer using them adopts.

**SELECTED EXERCISES**

Since in the design process students may be searching for properties throughout a course, a good introductory exercise may take the form of a sample project in the beginning of the term. The faculty member teaching the class collaborates with a liaison librarian and together they set up an assignment requiring students to select a material and search for properties for the project. The librarian provides instruction to show how properties are located or calculated. A research guide highlighting a number of useful sources will help students determine which sources are available for researching materials and material properties. Students work in small groups and search using the various tools and resources provided in the research guide. In consultation with the faculty member and liaison librarian, students identify candidate materials for their project. This search experience will be used as the basis for their project as the group continues to identify and experiment to find the right final materials.

**Exercise 12.1**

Ask students to imagine that they are preparing to design a wind farm near Atlantic City, New Jersey. The turbines will be designed for a salt air environment and constant exposure to ultraviolet (UV) radiation. What material properties will be most critical when designing the blades? Why?

Since windmill blades are essentially cantilever beams bending under wind pressure, both strength-to-weight and stiffness-to-weight ratios will be important design parameters. Material resistance to salt air corrosion and UV degradation will be important environmental concerns in the design process as well. Special coatings may be needed.

**Exercise 12.2**

Using the table feature in Microsoft Excel, have students brainstorm a list of possible materials based on the required physical properties for their project. Once they have the list of materials that will meet the physical requirements, have them start analyzing each material for the next criterion, such as environmental considerations and cost. Using the filter feature in the table, they can turn off all materials that are eliminated based on the next set of materials. They are left with only the materials that have not been eliminated showing, making it easier to rank and compare various materials. Have them repeat the process for each criterion until only the best candidates remain.

**Exercise 12.3**

Structural materials are usually selected based on their stiffness (resist deformation) and strength (will not fail). But we also desire that they be lightweight, especially in aircraft. Ask students what parameter best accomplishes these objectives, and where they would find that data.

**ACKNOWLEDGMENTS**

We appreciate the Drexel Smart House initiative and its contributions to this chapter about its experience with student projects in selecting proper materials during design and prototyping. Drexel Smart House is a student-led, multidisciplinary project to construct an urban
home to serve as a living laboratory for exploring cutting edge design and technology. Participants conduct research and develop design solutions aimed at improving the quality of life in urban residential settings. The program supports student innovation through early-stage research and the development of prototypes or models, with the ultimate goal of launching strong research and development for commercialization and technology transfer activities.

REFERENCES


