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Ramana M. Pidaparti

Design Engineering Journey

Springer

Design Engineering Journey

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Design Engineering Journey

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ABSTRACT

This book provides an introductory treatment of the design methodology for undergraduate students in multiple disciplines. It introduces the principles of design, and discusses design tools and techniques from traditional and multidisciplinary perspectives and comprehensively explores the design engineering process. Innovation, creativity, design thinking, collaboration, communication, problem solving, and technical skills are increasingly being identified as key skills for practicing engineers in tackling today's complex design problems. *Design Engineering Journey* addresses the need for a design textbook that teaches these skills. It presents a broad multidisciplinary perspective to design that encourages students to be innovative and open to new ideas and concepts while also drawing on traditional design methods and strategies. For example, students are provided with design solutions inspired by nature as well as the arts to nurture their creative problem solving skills. This book provides an overview from establishing need to ideation of concepts and realization techniques and prototyping, presented in an engaging and visually appealing manner, incorporating multidisciplinary examples that aim to reinforce the student's evolving design knowledge.

The technical level of this book is kept at an introductory level so that freshman and sophomore students should be able to understand and solve a variety of design problems and come up with innovative concepts, and realize them through prototype and testing. This book also can serve as a reference text for senior capstone design projects, and the readers will find that the examples and scenarios presented are representative of problems faced by professional designers in engineering.

KEYWORDS

design, engineering, innovation, problem solving, analysis, tools, techniques, design evaluation, product realization, design projects

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Preface

Design, engineering, and innovation are fundamental to many industries, and should be integrated and taught at all levels in the arts, business, and engineering curricula. There is a growing need for fundamental and introductory textbooks due to the fact that the technology is rapidly expanding and many topics need to be covered. This comprehensive book deals with the design engineering journey process and the use of design tools and techniques in the realization of the design. The design engineering journey book is appropriate for first- and second-year students as well as for senior capstone design projects, and is based on the author's experiences teaching design and senior capstone design projects over the past 25 years.

The book is compiled into nine chapters and provides an introduction to basic concepts along with case study examples to fully illustrate the design engineering principles and their applications. Each of the chapters provides enough details for students to understand basics and steps in the design engineering journey process. Design examples are provided that will help students to understand and apply concepts related to product design. Chapter 1 provides an introduction to design journey including good characteristics of good design, design failures/successes, details of engineering/product development, as well as the design thinking process. Chapter 2 describes several of types of designs, and problem-solving strategies. Brief descriptions of sustainability design, robust design, design innovation inspiration from nature, and the integration of arts, design, and nature, are presented. Chapter 3 describes the methodology of reverse engineering used to redesign products for better performance. Chapter 4 describes the steps of the design journey process, specifically the tools/techniques needed for identifying the design requirements. Chapter 5 provides an overview of concept design generation and evaluation techniques along with specific examples. Chapters 6 discusses the detail design and evaluation required in the design realization process and provides a comprehensive review of major design tools and techniques commonly employed. Chapter 7 discusses the reviews during the design journey process as well as the key communication and documentation processes of the design. In Chapter 8, the design realization process is discussed. In this section, CAD/CAM tools commonly used in design and manufacturing, as well as rapid prototyping and virtual engineering are also discussed along with a brief business plan that are vital to effective product innovation.

Sample design projects that further clarify the design engineering journey process and assist the student in understanding the strategies and techniques involved in designing quality products that are responsive to the needs of society are presented in Chapter 9. Several examples of interesting and challenging design projects are also presented.

Ramana M. Pidaparti
January 2018

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January 2018

CHAPTER 1

The Design Journey

After reading this chapter, you will be able to:

- Explain and define the term design
- Define the characteristics of good and flawed designs
- Explain the design journey process
- Explain different design paradigms
- Define multidisciplinary design and teams
- Understand the role of professionalism and the need to learn ethics

1.1 OVERVIEW

This chapter provides an introduction to design and its characteristics. Major design approaches, problem-solving steps, and characteristics of design teams are described. Design examples are also provided to illustrate salient features of the design journey process as well as design paradigms. Multidisciplinary design and design teams are briefly described. Attributes of technology graduates attractive to industry are also presented.

1.2 WHAT IS DESIGN?

When teaching design courses, instructors usually ask students to define the term "design." Typical responses include aspects related to innovation, solutions, creativity, teams, etc. When the author asked students in his sophomore design class to list as many words as they could think of that describe the term "design," the answers resulted in a *wordel* format presented collectively in Fig. 1.1.

There are many definitions of design. These include design as art, design as problem solving, design as a social process, and so on. The Accreditation Board for Engineering and Technology (ABET) is an organization which evaluates and accredits engineering curricula in the United States. According to ABET, engineering design is defined 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 engineering sciences are applied to convert resources optimally to meet a stated objective.

Figure 1.1: Words defining the term "design."

Among the fundamental elements of the design process are establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. The engineering design component of a curriculum must include at least some of the following features: development of student creativity, use of open-ended problems, development and use of design methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, and detailed system descriptions. Further, it is essential to include a variety of realistic constraints such as economic factors, safety, reliability, aesthetics, and social impacts.

1.3 WHAT IS ENGINEERING/PRODUCT DESIGN?

Engineering design is a scientific decision-making process used to meet specific societal needs such as construction of physical objects (aircraft, engines, bridges, medical devices, chemical plants, skyscrapers) or information systems (computer software, chips). The overall objective of any engineering design is to create a product/process/system that benefits society and also at the same time turns into an economic benefit.

The ability to design is both a science as well as an art, and combines analysis and synthesis methods. The scientific aspects of design can be learned through a systematic process (design methodology), problem-solving techniques, and through experiential learning. The artistic aspect of the design is gained through practice, by developing the ability to appeal to the aesthetic as well as technical design specifications. Engineers use their creative and imaginative skills along with scientific principles to develop efficient designs. Design skills are learned best by "*doing*," through first-hand experiences in developing and testing solutions to real-world problems.

In customer-oriented societies such as ours, consumers want products that function well, are sustainable, affordable, and aesthetically appealing. Moreover, the 21st century global marketplace has fostered the need to develop new products at a very rapid and accelerated pace. To compete in this market, companies must be very efficient in the design of their products. It is the design process that determines the effectiveness and efficiency of new product development. Therefore, college graduates today are expected to be able to address economic, social, environmental, aesthetic, and ethical considerations in designing products and services tailored to meet the needs of their clients. Today's consumer products have become so complex that most product development efforts require a multidisciplinary team of people with diverse areas of expertise to develop an idea into a product. Due to the involvement of large numbers of people in a multidisciplinary project, there is a greater need for ongoing communication and for establishing protocols and infrastructure to ensure that nothing important is overlooked and to maintain customer satisfaction.

1.4 DESIGN EXAMPLES

History is full of great design innovations. Some design examples of famous structures and buildings include, the Pyramids of Egypt, the Gothic cathedrals of Europe, the Great Wall of China, the Taj Mahal of India, and many others. Engineering designs can also be found in our daily lives. For example, products we use everyday such as the iPhone, iPad, and DVD players, soda cans, coffee makers, toasters, grinders, peelers, bicycles, chairs, paper clips, cars, motorcycles, airplanes, helicopters, wheel chairs, robots, exercise machines, and so on are all the result of quality product designs. A simple gadget like a personal DVD player contains many intricately designed components such as motors, mechanisms, lasers, electronics, gears, switches, optics, LCD, etc.

Several design application examples from various disciplines (biomedical, civil, aerospace, mechanical, electrical and computer, and industrial) are presented in Fig. 1.2. It can be seen from Fig. 1.2 that a lot of creativity and innovation goes into the design of many engineered products.

1.5 WHAT ARE CHARACTERISTICS OF A GOOD DESIGN?

Figure 1.3 shows graphically that a design need is fulfilled through multiple solutions following various design process paths. The design process path depends on the designer's knowledge of the design process and also domain knowledge. The domain knowledge comes from studying different disciplines, say engineering (where students takes courses in physics, math, engineering

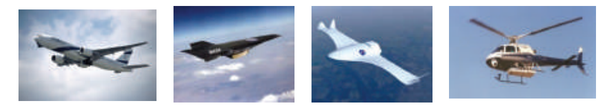
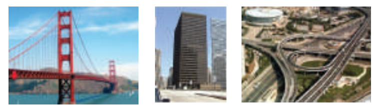
Aerospace	
Biomedical	
Civil	
Electrical/ Computer	
Industrial	
Mechanical	

Figure 1.2: Examples of designs from multiple disciplines affecting our daily lives (Courtesy of Nokia, DeWalt, Boeing, Lockheed, Intel, Sony, NASA, Clarks Orthopedic, Honda, Filmetrics, Ferrari, JJS, Bell).

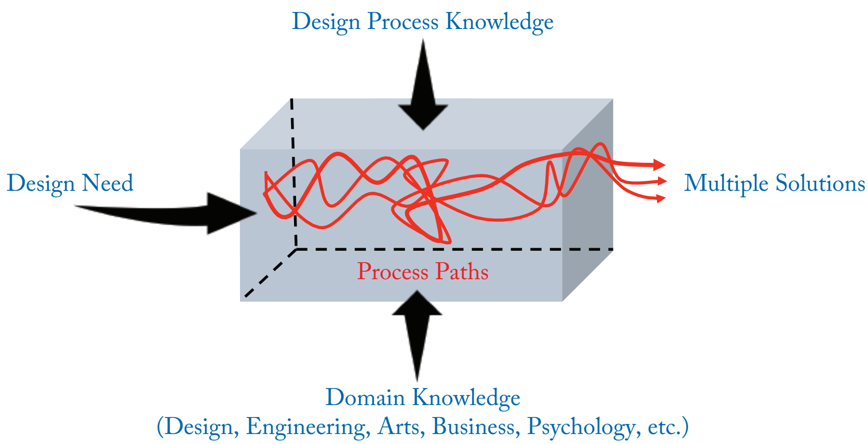


Figure 1.3: Design leads to multiple solutions following multiple process paths for the same need/problem.

sciences, materials, manufacturing, kinematics, economics, mechatronics, etc.). Similarly, art students go through various design studio courses as well as metal, wood working, along with other courses as part of their discipline. In general, different process paths will lead to different solutions for the same design need/problem. One of the main goals in the design process is to find a good solution with minimum cost and resources and that at the same time meets the customer needs.

From the perspective of companies and investors, the designed products should yield profit by offering a quality product at an affordable price to consumers. The characteristics that measure the effectiveness of a product design are as follows.

Quality — How good is the product from the customer's point of view (does it satisfy needs, is it robust and reliable, looks great, and does it have the best selling price)?

Cost — What is the manufacturing cost for producing each unit, and how much profit can the company make after accounting for marketing and sales and discount?

Time to Market — How quickly can the design team bring the product from its initial concept to final product to the market?

Impact – Social and Environmental — What impact does the design have on society? What is the environmental impact (sustainable and eco-friendly) related to the design life cycle?

The time and money required to develop a new product to market depends on the type of product. A few products can be developed within a year, while many require 1–3 years, and some take as long as 3 years or more, such as the Boeing 7E7 aircraft, and recently, the Boeing 787 Dreamliner. It has been estimated that flaws in the design process contribute to up to 85% of the problems with new products that do not work as they should, that take too long to bring to the market, or cost too much. Also, the designs may fail due to poor understanding of the problem, not making realistic assumptions, incorrect design specifications, poor choice of materials (plastic instead of metal), or faulty manufacturing (large tolerances and poor quality control).

1.6 ENGINEERING DESIGNS AND FAILURES

Throughout history there have been many design successes and design failures. These are briefly described below. But before we discuss them, consider this guiding question.

What makes some designs succeed while others fail?

We need to look into the history of designs and often the answer is related to how complex the design is and whether all of the requirements are met in the final design.

What are the primary causes of engineering failures/disasters?
Here are some examples:

- Human Factors
- Design Flaws
- Materials Failures
- Extreme Conditions
- Combinations of the above

Human Factors: The Three Mile Island nuclear disaster (shown in Fig. 1.4), involved a valve that was broken and there was rampant confusion about whether or not it was fixed, and people failed to communicate progress with each other. A simple failsafe fail resulted in one of the worst disasters in nuclear history. Variable elements, like humans, in complex systems design make things all the more difficult.

Design Flaws: Sure, the Titanic struck an iceberg as shown in Fig. 1.5, but had the ship's ballast and hull surrounding the engine been shaped better, the impact wouldn't have been as devastating. In the future they will account for this design flaw when building the Titanic II.

Materials Failures: In the Oklahoma City Bombing, a car bomb blew up columns in the federal building. The fail safe was to have load fall on single point, but the concrete was not strong enough to handle all the load, and exacerbated the damage (see Fig. 1.6). Obviously the car bomb had something to do with causing material failures, but the damage wouldn't have been as bad with better material choice. Terrorism is now a factor in materials choice and building construction.

Extreme Conditions: The Tacoma Narrows Bridge was made to be the longest suspension bridge of its time, but it didn't account for the danger of extreme winds, and resulted in twisting and partial collapse as shown in Fig. 1.7. This led to more engineers taking into account the importance of wind in their designs, like the Brooklyn Bridge.

Combination of the Above Situations: The BP Oil Spill involved human error, design flaws, extreme conditions, and materials failure, as shown in Fig. 1.8. Insufficient knowledge and uncertainty are the biggest factors in engineering design failures.

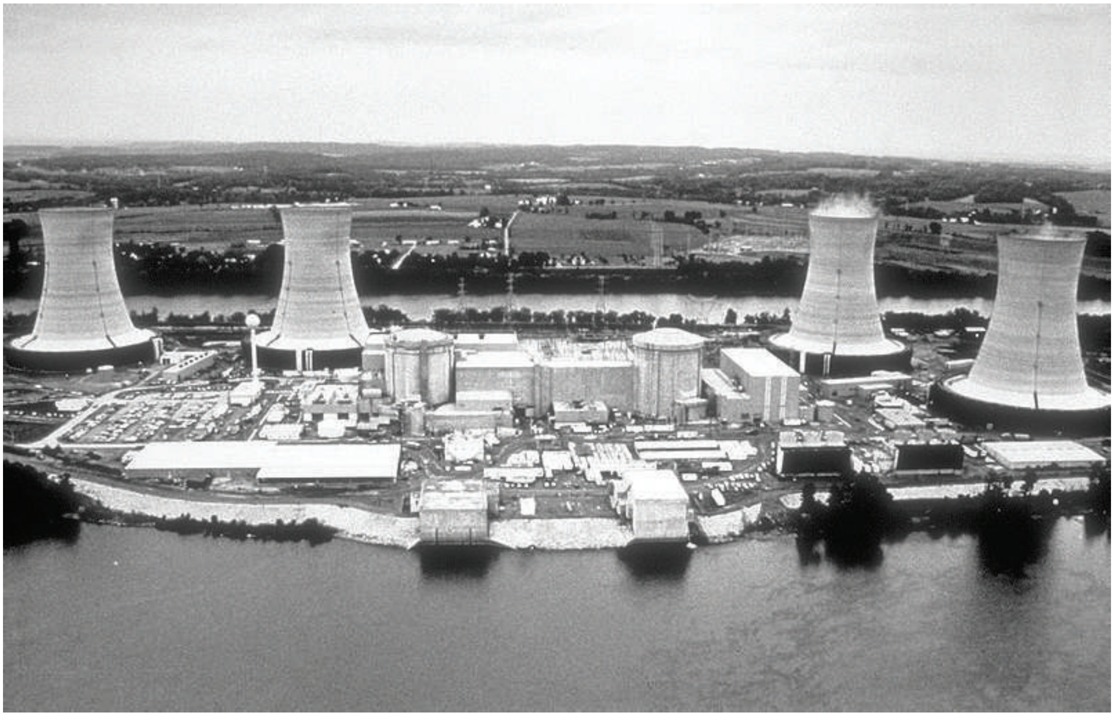


Figure 1.4: Three Mile Island nuclear disaster (www.google.com/images).

Figure 1.5: Titanic ship wreck disaster (www.google.com/images).

Figure 1.6: Oklahoma city bombing (www.google.com/images).

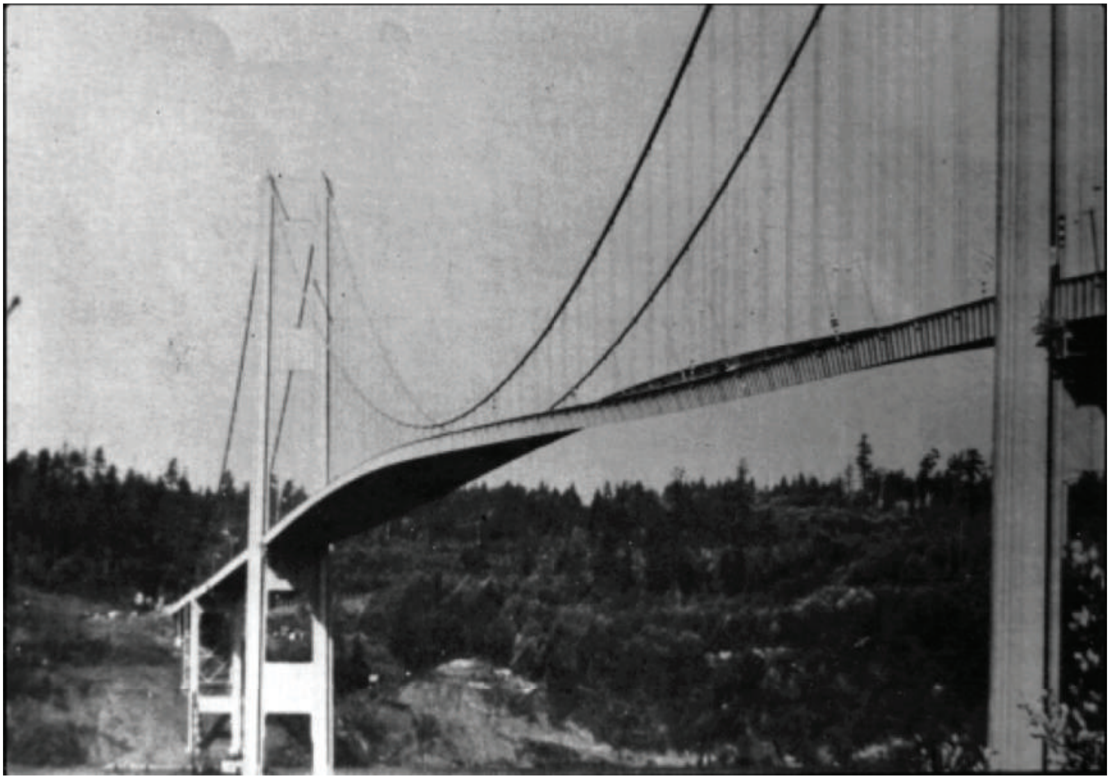


Figure 1.7: Tacoma narrows bridge disaster (www.google.com/images).

Figure 1.8: BP oil spill disaster (`www.google.com/images`).

1.7 THE DESIGN PROCESS JOURNEY

The design process is a journey that relies on our ability to communicate our ideas through a series of steps for the development of a project. The design process varies from product to product, and industry to industry. In order to develop new, innovative, and competitive products, the design engineer has to develop creative skills and strong analytical capabilities, and employ a systematic methodology. Even though several authors have defined and variously named key steps/stages in the design process, it is possible to present a generic process of the activities involved in the design process to meet design goals related to societal, environmental and business needs.

Designing a new product involves completing specific tasks and objectives corresponding to several design phases over time, starting from establishing a need to designing a product to the realization of the product. The various steps involved in the design journey process are discussed in detail in Chapter 4. The overall product design process involves five different phases, as shown in Fig. 1.9. The major aspects of each of the phases are briefly presented below.

PHASE 1: ESTABLISH NEED

The "Establish Need" phase deals with identifying customers/stakeholders and their needs, and developing requirements for designing a product/system. The design journey process begins with customers or marketing or sales personnel identifying a need. Needs may be related to consumer

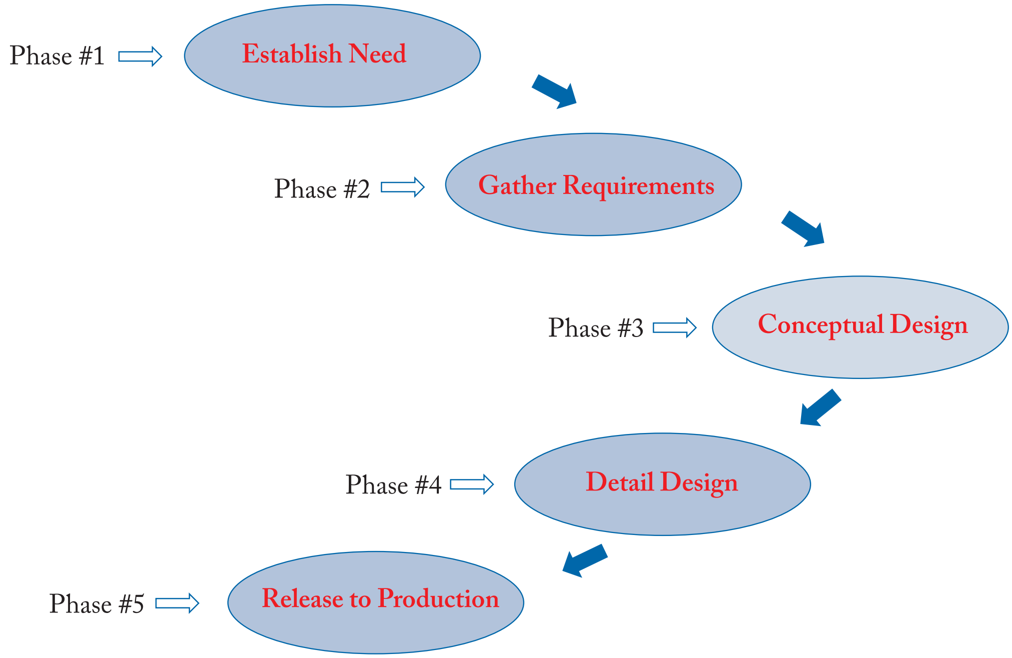


Figure 1.9: Overview of various phases in the product design process.

demand for products and services which may be driven by industry's desire to produce profits. Also, needs may arise as a consequence of federal or state or local government policies, military regulations, new technologies, business strategies, or sustainability concerns. In any case, it is usually not the designer who initially identifies the need to be satisfied, as shown in Fig. 1.10.

Figure 1.10: Phase 1 of the design process journey—Establish Design Need.

PHASE 2: GATHERING REQUIREMENTS

This phase deals with the task of understanding who the stakeholders are, and gathering requirements for what the stakeholders want, and defining design/project objectives, as shown in Fig. 1.11. This is very essential prior to translating the customer's needs into a conceptual form that will ultimately lead to a satisfactory design solution. The design may be subjected to constraints such as available budget, time, personnel, materials, manufacturability, legal/ethical factors, and competition. In this phase of the design process, it is very critical that the designer work with the customer to ensure that end user needs are truly understood. In practice, defining the problem requires regular communication between clients, users, and designers. Typical design criteria in defining engineering requirements include cost, quality, reliability, maintainability, aesthetics, safety, human factors, environmental and societal impact, and others.

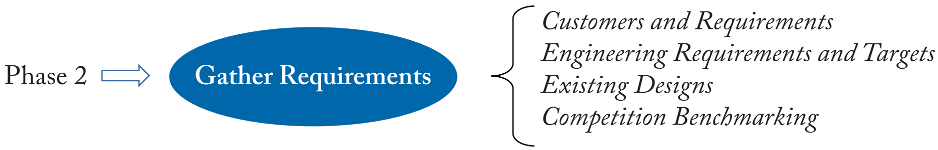


Figure 1.11: Phase 2 of the design process journey—Gather Requirements.

PHASE 3: CONCEPTUAL DESIGN

This phase deals with the task of generating candidate concepts, and analyzing and evaluating them, as shown in Fig. 1.12. Brainstorming is one technique commonly employed by design teams to generate many alternate solutions. After several concepts are generated, they are evaluated against the customer requirements to identify one or two concepts that will receive further consideration in the product design phase. The conceptual design phase is the most critical and important part of the design process. There is maximum flexibility for design changes during the conceptual design phase, with the lowest impact on cost.

Figure 1.12: Phase 3 of the design process journey—Conceptual Design.

PHASE 4: DETAIL DESIGN

During this phase as shown in Fig. 1.13, detailed analyses for deformation, stress analysis, heat transfer, failure, design for manufacture, design for assembly, safety, cost, etc. are performed. In this phase, it is the design team's responsibility to come up with product details including, geometry, dimensions, materials, manufacturability, assembly, and various drawings for manufacturing, and cost analysis. The designer may use several types of designs (configuration design, parametric design, robust design, sustainability and green design, and others) in the design process.

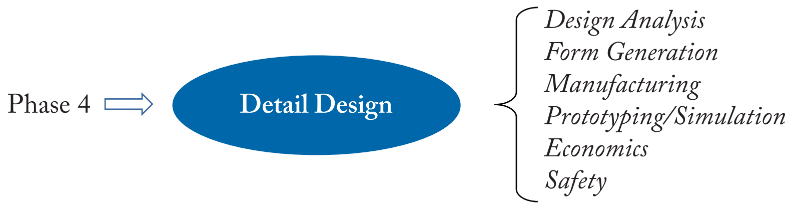


Figure 1.13: Phase 4 of the design process journey—Detail Design.

PHASE 5: RELEASE TO PRODUCTION

After the detailed design and manufacturing phases of the product are completed, the product is released to production, as shown in Fig. 1.14. In this phase, the issues of quality control and maintenance are discussed. The product is retired or recycled after the product is in use for the designed life.

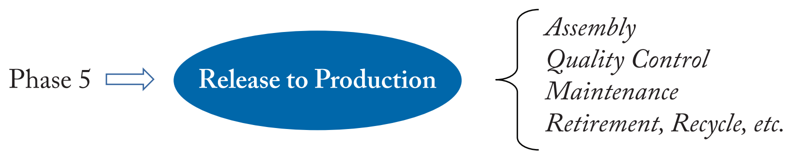


Figure 1.14: Phase 5 of the design process journey—Release to Production.

1.8 WHAT IS DESIGN THINKING?

Design thinking is a human centered innovation process focused on producing innovative/creative solutions. One of the key differences from conventional design is empathizing with the customer, which means putting oneself in the customer's shoes. It takes designers/engineers out of their comfort zone, and puts them in the field to experience and become emotionally involved with a design problem. Design thinking promotes a more open minded approach where designers collaborate with customers as well as people from other disciplines that aren't normally involved in the design. Design thinking promotes an accelerated innovation process through crude prototyping, failing fast to learn faster, and quicker reaction rather than formal processes. Design thinking connects people and businesses using design as a medium. The differences between conventional design and design thinking are presented in Table 1.1 below.

Table 1.1: Comparison of conventional design vs. design thinking

Conventional Design	Design Thinking
What solution will satisfy this design problem?	Empathize with the customer. What do they really need?
Using technical specifications and market research as a starting point for the design.	Start by observing, experiencing, and understanding the problem/application in the field.
Cross-functional collaboration.	Including customers in the design process as much as possible and soliciting participation from unconventional sources.
Designer knows best.	Involve everyone, not just designers.
Analyzing and perfecting through incremental improvements.	Emphasis on radical innovation. Prototyping and failing quickly to speed up the learning process.
Majority of the design focus is on product features and performance.	Greater emphasis on understanding the entire product life cycle and all of its implications.

The design thinking process is similar to the design process journey, as shown in Fig. 1.15. It has five phases which include empathy, define, ideate, prototype, and test. In general, design thinking is a process mostly adopted by designers and it is how a designer thinks and pursue a solution to meet the customer need. It is also similar to scientific thinking but the designer address a problem defining and focusing questions based on insights from empathy. Human centered discussions are used to come up with design solutions that address problems that are imperfect or incomplete.

Design thinking approaches also offer the opportunity to comprehensively assess the strengths and weaknesses of a proposed design idea or concept prior to moving to the prototyping phase in the design process. The ideation process is typically not complex or expensive but requires modeling and testing a physical prototype as many times as needed (test, re-prototype, re-test, re-prototype for example) to ensure that the final prototype is as close to being perfect as possible and meets consumer needs.

Apple's product design and development process is widely admired and recognized for its high success rate and reputation for quality products. Spearheaded by Steve Jobs, the product development process typically is systematic and detailed and outlines the roles and responsibilities of all the personnel involved in developing, designing and producing a new product. The design team selected to work on a specific product for example comes up with its own reporting structures and works directly with the executive team. Once a product is designed, a prototype

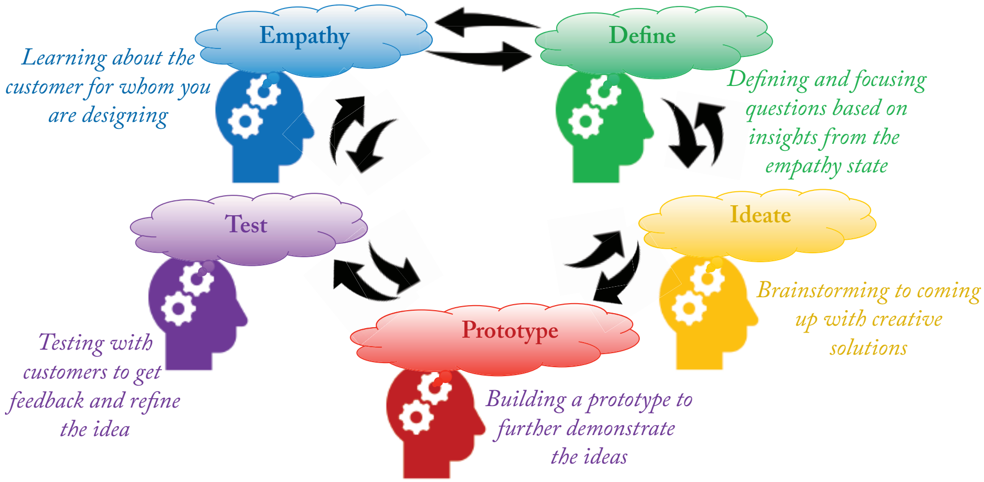


Figure 1.15: The design thinking process.

is developed and is tested and reviewed iteratively. This cycle is also implemented throughout the manufacturing process to ensure that the Apple product launched is both cutting edge and offers a high quality consumer experience.

Kaiser Permanente used design thinking to solve a problem related to information flow between nurses during shift changes. It did not have an effective system for recording and organizing patient care information that could be easily accessed by the various nurses providing care during different shifts. The design thinking approach helped them understand and better address this critical gap in providing patient care during different shifts by nurses.

Shimano is another example of a company that used design thinking to come up with innovative design solutions and carve a unique niche for itself in the bicycle parts market. Through extensive consumer research including input from novice bikers on social media, Shimano realized that it was very important to address both performance and ease of use in manufacturing bicycle parts. Shimano also used discussions with consumers prior to launching their brand and ensured that the purchasing experience was user friendly.

Other specific examples include design thinking for X (social good, mobility, educators, teaching kids, innovation) in which each of the projects deals with the design thinking process to deliver an innovative solution.

1.9 WHAT ARE PRODUCT DESIGN PARADIGMS?

The product design process involves the organization and management of information and people to develop ideas into quality products. Basically, it is a problem-solving method that transforms a poorly defined problem into a complete functioning product. Product function, product form, manufacturing processes and materials are the important controllable variables in engineering product design. Due to the complexity of products and manufacturing processes today, several different people are required to design and fulfill roles in marketing, engineering, and manufacturing. Historically, variations in how the design and manufacturing activities are conducted throughout the design process have led to the following two major approaches to engineering design.

OVER-THE-WALL DESIGN APPROACH

In the over-the-wall design approach, also known as conventional design, each group (customers, marketing, design engineers or manufacturing) involved in the design is separated (or walled off) from the others. Figure 1.16 shows the overview of the over-the-wall design approach. It can be seen from Fig. 1.16 that the design process begins with the customer needs being thrown over the metaphorical wall (one way) to the marketing group. The marketing group then establishes its perceived market needs and in turn, transfers or throws this marketing need to the design engineers. The engineering team interprets the market needs to be used in developing and refining concepts into manufacturing specifications. Finally, the manufacturing group interprets the specifications and builds what it thinks the previous group (engineers) wanted. Frequently, the separation and lack of interaction between the groups leads to misunderstanding of what the previous group wanted. Not only is additional time required in clarifying the needs of the previous group, more time is unnecessarily used if a group along the way makes a poor decision that inadvertently affects another group's ability to be efficient, or more importantly, a product that doesn't work effectively or perform its task. Due to the inefficiency of the over-the-wall design approach, the concurrent engineering approach was developed and is the preferred engineering design approach today.

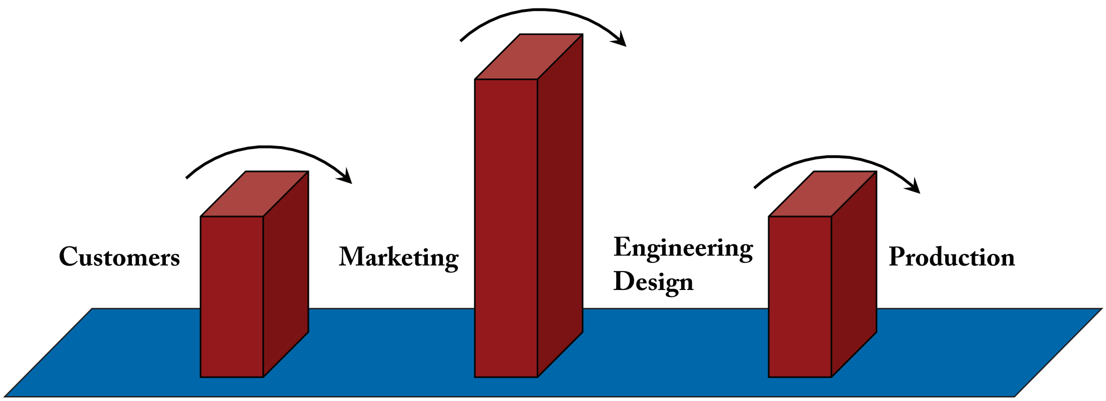


Figure 1.16: Overview of the over-the-wall design approach (conventional design).

CONCURRENT ENGINEERING APPROACH

Concurrent engineering, also known as parallel design method, brings together teams of people with tools and techniques needed to effectively integrate product and process design. In concurrent engineering, all stakeholders involved in the development of a product are an integral part of the design team and are involved in every stage of product development from identifying the need for the product to manufacturing the product, and finally, recycling or retiring it as appropriate. Design teams today need representation from various professionals (with expertise in marketing, materials, project management, manufacturing, etc.) to effectively handle the ever increasing complexity of products and manufacturing processes. As design teams become more inclusive, timely and accurate information sharing becomes even more critical to the success of the design project. Consistent communication (sharing the right information with the right people at the right time) throughout the life cycle of the product will be one of the most important indicators of the quality of the product. Several tools and techniques including computer based approaches may be used in sharing information between members of the design team who are simultaneously evaluating progress on product development and manufacturing processes.

An overview of the concurrent engineering approach to product design is shown in Fig. 1.17. This approach was created to address ten features built around integrating the product, information/tools, and people. These features (Ullman, 2015) [24] include:

- Focus on the entire product/design life
- Use and support design teams
- Realize that the process is as important as the product/design
- Attend to planning for information-centered tasks
- Carefully develop product/design requirements
- Generate multiple concepts and evaluate
- Be aware of the decision-making process
- Attend to quality during each phase of the design process
- Simultaneously develop product and manufacturing processes
- Emphasize communication—key information provided to the right people at the right time.

Independent of which design approach is used, the success of a design process is evaluated in terms of the cost of the design, design effort, quality of the final product, and the time needed to develop the product. All evaluated criteria have some unit of account, whether it is the amount

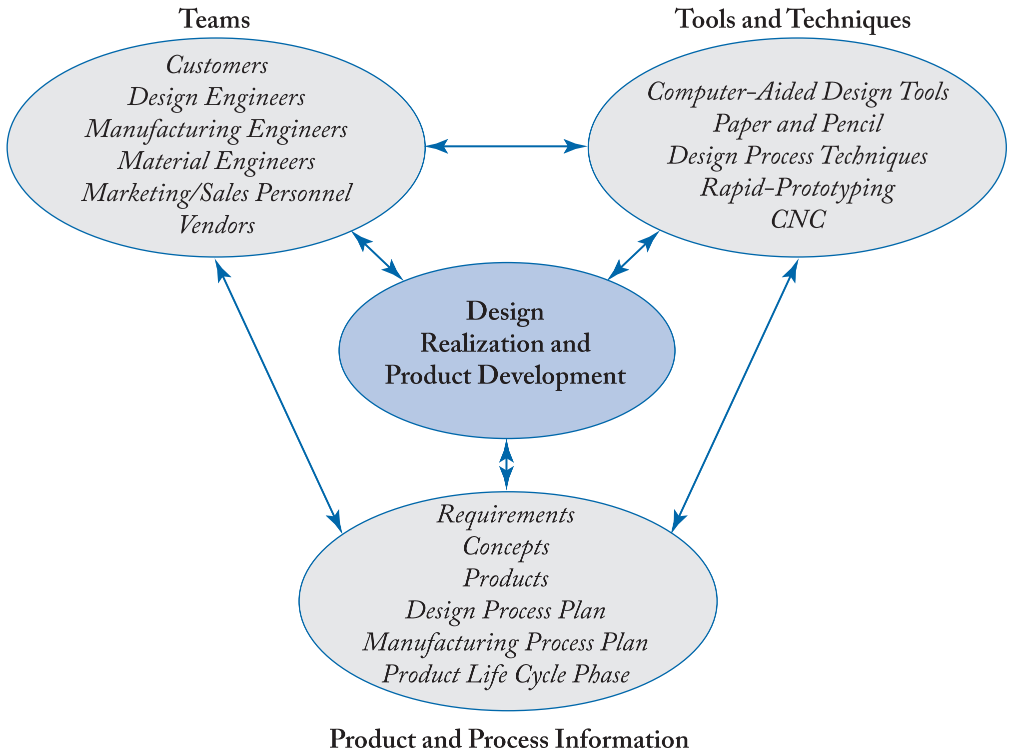


Figure 1.17: Overview of the concurrent engineering approach.

of time, and/or dollars, with the exception of quality. Quality is determined by asking the customers questions such as does the product work as it should, how long should it last, how does it look, is it easy to maintain/repair, etc. The consumer responses can then be evaluated in terms of the product's performance and engineering targets may now be measured in terms of time and cost. Survey results of various industries including Boeing, Toyota, Ford, and others showed that the concurrent engineering approach can reduce the time to market by 60%, improve return on assets by 70% or higher, and improve overall product quality by 350% or higher.

Case Study In order to better illustrate the product design process, a simple design example is discussed in detail below.

Example – Paper Clip Design

Let us consider the design of a paper clip, a common office product we are all familiar with. How would you go about designing this simple gadget that has no moving parts? The answer may lie in following the basic design process.

Need: To have a gadget that can hold a few pieces of paper together and not spoil or tear the papers.

Requirements: It should be inexpensive, reusable, compact, easy to use, and rust proof.

Possible Design Idea: May be made from a single piece of rust resistant wire with no sharp edges and with a pointed end toward the papers so that the clip can slide on to them.

Manufacturing Method: A fixed length of wire can be bent around posts of two slightly different radii.

Possible Materials: Steel, iron, wood, plastic, and others. Iron may have enough strength, but may corrode so it needs to be coated with rust protection. Other possibilities include wood and plastic. Some materials (steel) are stiffer than others (plastic or wood). Depending upon the usage, if only a few pages are inserted, then the material springs back to original shape. But if many pages are inserted, then the clip material may undergo permanent deformation and may not return to its original shape. With repeated use, eventually, the clip may break.

There are many design changes that are possible. One design idea may be to make the tip of the inner loop slightly bent out of plane, another may consider a different tip shape, different ends design, etc. It is interesting to note that the first patent for a paper clip was filed in 1899, and the latest one in 2003. Some of the patented paper clip designs are illustrated in Fig. 1.18. The GEM paper clip was first invented in 1899, and then improved in 1920. The common double overlap shape manufactured by GEM Manufacturing Ltd., of England is still used today. Paper clips today come in many shapes, materials, and colors.

Imagine that you are required to improve the design so that the paper clips are easily inserted, hold pages securely, are lightweight, and won't break. What other design ideas would you consider? Keep thinking about it, and you will come up with many possibilities.

1.10 MULTIDISCIPLINARY APPROACH TO DESIGN

In the concurrent engineering approach, the emphasis is on the product life cycle and may involve only one discipline (mechanical engineering or civil engineering or electrical engineering or other disciplines) in the overall design process. This may lead to the absence of optimization in the design process. In contrast, people from multiple disciplines (e.g., mechanical, business, arts, education, psychology, electrical, chemical) may work toward understanding the design problem and find a solution. Multidisciplinary design and optimization is a new technology in engineering systems that exploits the synergism of mutually interacting phenomena. The integrated design process under the multidisciplinary approach will improve the design quality and reduce the design cycle time and cost.

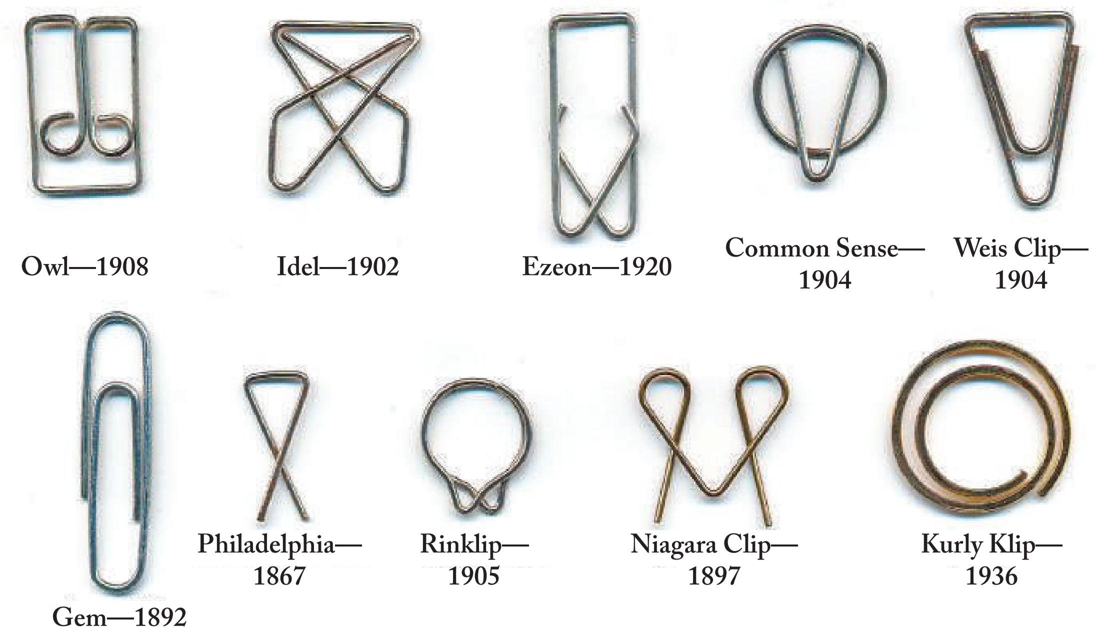


Figure 1.18: Paper clip designs over the years (sources: `http://www.officemuseum.com/paper_clips.htm` and `http://www.wipo.int/ipdl/IPDL-CIMAGES/view/pct/getbykey5?KEY=03/66350.030814`).

In order to develop designs that address societal needs and to have greater impact, design solutions need to be arrived at through multidisciplinary teams including marketing, engineering, and design in order to add a value or benefit to the product, as shown in Fig. 1.19. Through the use of a multidisciplinary approach to product design, customers can have products that are useful, usable, and desirable. The multidisciplinary approach to design has recently gained wide acceptance in the aerospace industry. Figure 1.20 shows the multidisciplinary approach to aerospace systems design. This approach is currently being implemented in many other product applications.

1.11 MULTIDISCIPLINARY DESIGN TEAMS

The increase in size, complexity, and importance of products has made the product development process more reliant on effective team dynamics and teamwork. Successful product development may require many different talents and skills from business, psychology, art, and engineering.

The success of a multidisciplinary design team is attributed largely to the ability of individual members to be highly motivated and to be cooperative, and to regularly communicate

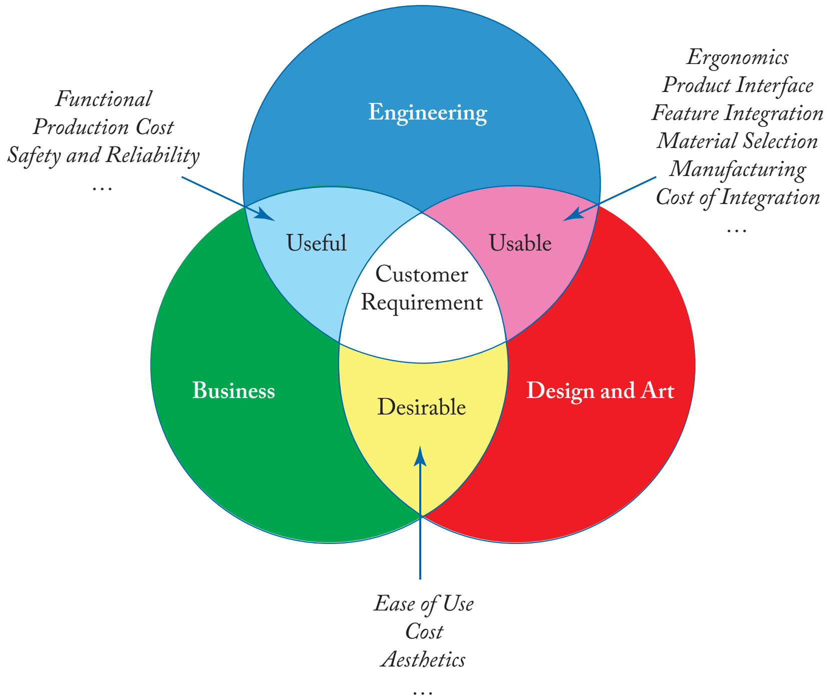


Figure 1.19: Multidisciplinary approach to product or system design.

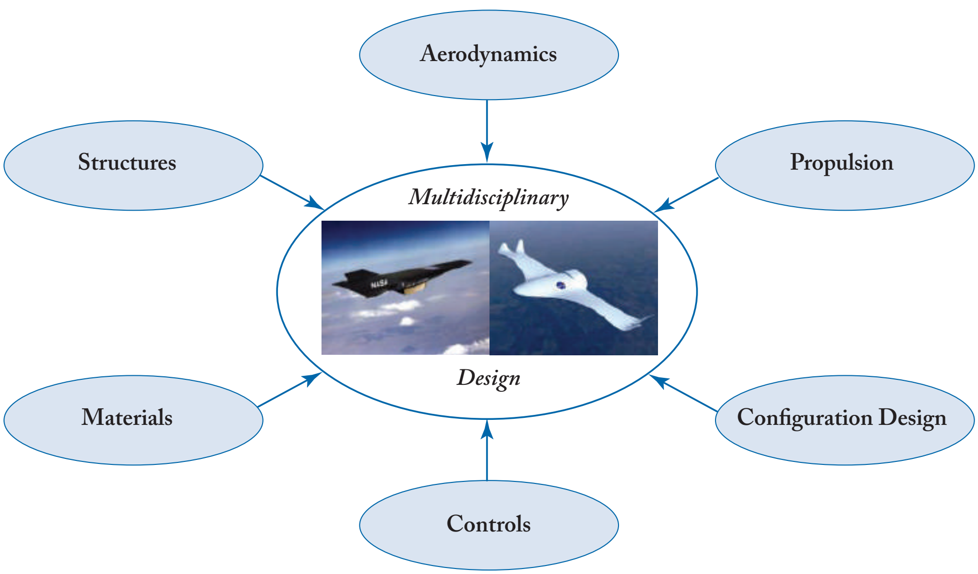


Figure 1.20: Multidisciplinary approach to aerospace systems design.

ideas and decisions to the right people at the right time. The effective characteristics for making group decisions as well as functioning efficiently in a multidisciplinary team are given below.

- Have a clearly defined and set objectives/goals
- Understand and commit to customer's expectations
- Make decisions effectively based on facts/data/information
- Communicate effectively to resolve any conflicts in a timely manner
- Freely express ideas and feelings
- Continuously monitor the performance and make improvements

The following are the responsibilities of some of the members in a product development team.

- Product Design Engineer—Has an engineering background and is responsible for the primary design of the product.
- Product Manager (Marketing Manager)—Has a sales background and is the liaison between the customer and the design team.
- Manufacturing Engineer—Has a manufacturing background and provides useful input about the facility's manufacturing abilities and the potential costs.

In addition to the product design engineer, product manager, and manufacturing engineer, depending on the size of the design project, additional personnel may be included as necessary. These include a drafter, materials specialist, artist, psychologist, detailer, quality control/assurance specialist, industrial designer, assembly manager, technician, vendors, etc.

- Drafter—Uses computer-aided tools to develop drawings of the components.
- Artist—Uses creativity skills to develop innovative ideas.
- Materials Specialist—Has a thorough knowledge of materials to aid in appropriate selection.
- Machinist—Aides in the creation of tooling and prototypes.
- Detailer—Finishes up the design and provides the assembly and manufacturing specifications.
- Business Manager—Uses marketing and management skills to develop market strategy and business plan for the product.

- Quality Control—Inspects the incoming raw materials, components produced, and the final product to ensure not only quality but also that the product is up to current codes and standards.

- Technician—Performs tests to insure that the engineering and performance specifications are met.

1.12 ENGINEERING PROFESSION

The Engineering profession is a noble one. It is dedicated to systematically developing and applying technology for the benefit of society. The engineer/product designer should take responsibility for the design decisions, and remain dedicated to using his/her talents to benefit humanity. The engineer may have to take on many roles as a statesman, an artist, and a humanitarian. Engineers usually work in many roles as a sales/marketing engineer, design engineer, manufacturing engineer, materials engineer, application engineer, and others.

The term "profession" rather than occupation or job is used to refer to the practice of engineering, as it requires formal education and advanced skills as well as the exercise of judgment and discretion and results in positive public service outcomes. Standards for admission to the profession are established by specialized agencies and members are expected to abide by certain basic rules and regulations governing their conduct, particularly in their roles as professionals. Essentially, engineers are expected to abide by a "code of ethics" that outlines their rights, duties and obligations as members of the profession. Knowledge of the profession's ethical principles will help the practicing engineer make informed judgments in situations where they may be a conflict between government and company regulations and public safety and environmental protection considerations, for example.

CODE OF ETHICS

Professional ethics/codes are often broad based in nature and do not necessarily address every dilemma that may arise during the course of work activities. However, they are intended to provide a starting point for ethical decision making. When designing a complex project, there are many decisions that need to be made which may affect all stakeholders. To help to make the decisions, several professional engineering organizations (ASEE—American Society for Engineering Education; ASME—American Society of Mechanical Engineers; ASCE—American Society of Civil Engineers; IEEE—Institution of Electronics and Electrical Engineers; ABET—Accreditation Board for Engineering and Technology; and NSPE - National Society of Professional Engineers) have developed their own code of ethics. These codes should be used as guidelines when faced with a dilemma in making a decision and sometimes require further research and discussion among all stakeholders involved in the design project.

A couple of examples of "code of ethics" from ABET and NSPE websites are given below and students are encouraged to visit the websites for better understanding.

- *ABET Code of Ethics for Engineers* (www.abet.org)
- *NSPE Code of Ethics for Professional Engineers* (www.nspe.org/resources/ethics/code-ethics)

CASE STUDIES

The ethical skills can be practiced by going through case studies that are available given below.

- From National Society of Professional Engineers, NSPE Board of "Ethical Review Cases," website: www.nspe.org/resources/ethics/ethics-resources/board-of-ethical-review-cases
- From National Academy of Engineering, "Cases and Scenarios" Online Ethics Center for Engineering, website: http://www.onlineethics.org/

1.13 ATTRIBUTES OF A DESIGN ENGINEER ATTRACTIVE TO INDUSTRY

In order to be marketable in engineering industries, every product designer/engineer should be aware of the attributes discussed below (http://www.boeing.com).

- A good grasp of engineering science fundamentals.
  - Mathematics (including statistics), physical and life sciences
  - Information technology
- A good understanding of the design process and manufacturing (i.e., understand engineering).
- A basic understanding of the context in which engineering is practiced.
  - Economics, history, legal aspects, environment
  - Customer and societal needs
- Good communication skills.
  - Written, verbal, graphic
- High ethical standards.
- An ability to think both critically and creatively, independently and cooperatively.
- Flexibility—an ability and the self-confidence to adapt to rapid/major change.
- Curiosity and a desire to learn—for life.
- A profound understanding of the importance of team work.

1.14 EXERCISES

1.1. What is engineering design and why should we study it?

1.2. Identify five design problems from everyday life.

1.3. What are the major design approaches? Discuss their advantages and disadvantages.

1.4. Select a product and determine the design objective. Discuss how the design can be improved so the product can have multiple functions.

1.5. Find four examples of designs and describe the design process steps.

1.6. Find design examples related to civil engineering, mechanical engineering, and aerospace engineering and discuss the design process steps unique to each discipline.

1.7. Find examples of multidisciplinary design related to arts, business, and engineering.

1.8. Discuss the stages involved in designing an electro-mechanical toy for children. What disciplines should be involved in the design team?

1.9. What are engineering ethics and why should you learn them?

1.10. Review the ASME Code of Ethics and list two principles.

1.11. Discuss a case study from the NSPE Ethical Review of Cases.

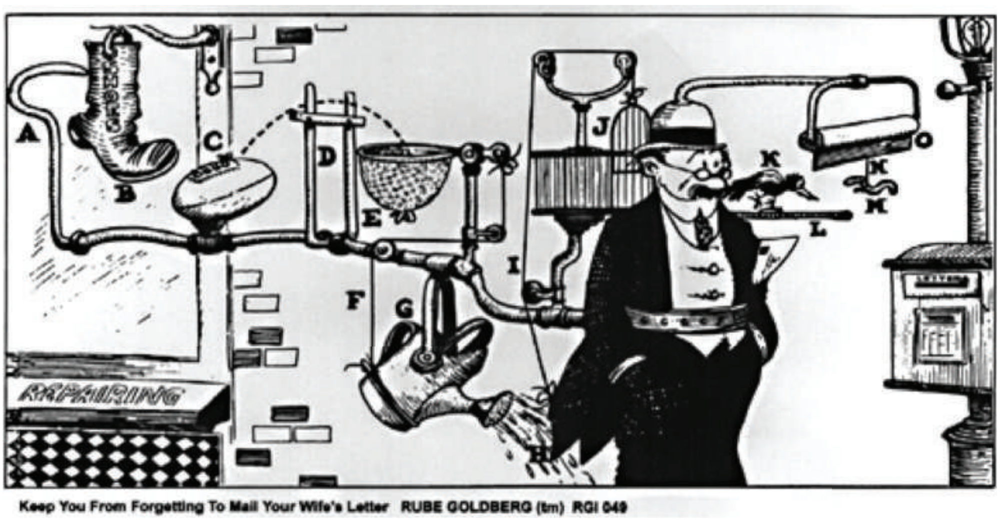


Figure 1.21: Drawn by 20th century cartoonist Rube Goldberg (1883–1970), studied engineering at UC Berkeley and then became an artist (source: http:/www.bethpage.ws).

CHAPTER 2

Solving Design Problems

After reading this chapter, you will be able to:

- Explain the differences between analysis and design problems
- Explain various types of design problems
- Apply design problem solution strategies
- Explain robust design characteristics
- Explain sustainability and green design characteristics
- Explain nature-inspired design
- Explain how design ideas can be explored using nature/art

2.1 OVERVIEW

This chapter introduces the differences between analysis and design, various types of design problems and a general problem solving methodology. Robust design, sustainability and green design, and design inspired by nature and art are also presented. Strategies for solving design problems are also discussed.

2.2 DESIGN VS. ANALYSIS

Design problems are open-ended, where more than one feasible solution may exist. The goal of design problems is to find a solution to meet a set of requirements (see Fig. 2.1). On the other hand, analysis involves using the laws of mathematics, physical and chemical sciences to find a solution for a given set of data/design (see Fig. 2.1). The word "analysis" can also be applied to problems that predict or validate the results of an experiment using mathematics. The following examples further illustrate the differences between design and analysis.

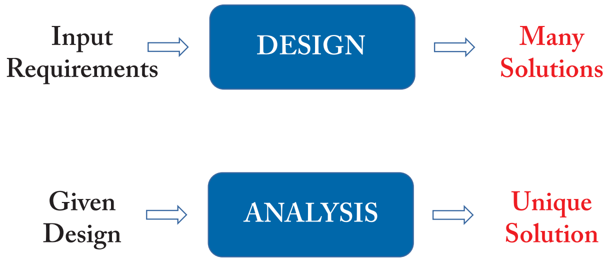


Figure 2.1: Design vs. analysis—differences.

EXAMPLES OF DESIGN PROBLEMS

Design a water bottle to hold enough water for a day when traveling in the mountains. Another example, design the tallest tower possible with three pieces of paper, ten paper clips, and one scotch tape. Both the problems are open-ended in that many solutions exist. The design process involves problem formulation, solutions generation, and evaluation. The characteristics of design problems are summarized below.

DESIGN PROBLEMS – CHARACTERISTICS

- Problem statement is incomplete, ambiguous, and self-contradictory. It is less precise. It needs more information and/or has to make assumptions to find a solution.
- Problem does not have a readily identifiable closure. There are many possible solutions using different scenarios.
- Solutions are neither unique nor compact. There are many possible answers based on the assumptions.
- Problem requires integration of knowledge from many fields. These include science, mathematics, design, art, mechanics, etc.

Analysis helps to make decisions and guide the design process. A design project without analysis is like a class without a teacher or basketball team without a coach. Usually, the analysis process involves: (i) formulating (understanding the problem and having plan for a solution); (ii) solving (figuring out unknowns using mathematical methods and equations); and (iii) checking (accuracy, precision, and validation). Different types of analysis are required at different stages of the design process. The characteristics of analysis problems are summarized below.

ANALYSIS PROBLEMS – CHARACTERISTICS

- Problem statement is compact and well defined. It is complete, unambiguous, and with no contradictions.

- Problem has a readily identifiable closure. It is easy to recognize that an answer is obtained.
- Solution is unique and compact. There is a single correct answer.
- Problem uses specialized knowledge. They require the use specific knowledge related to the problem.

EXAMPLES OF ANALYSIS PROBLEMS

Consider the design of most robust and giant ship "Titanic" of the early 1900s. The giant ship sank when its starboard side was punctured by an iceberg, causing the hull to fill with water and tip the ship. This was due to designers not considering the dynamic analysis which takes into account external forces due to choppiness of the sea, and the unbalancing movement of a collision with an iceberg. At the same time, engineers considered only static analysis during the design of the ship, meaning the ship was assumed to be stationary and considered only the weight of the passengers, cargo, and wind forces.

Another example of successful engineering analysis is the development of modern aircraft, where engineers developed better approaches for the design analysis of airplanes under a dynamic environment. In engineering and technology, analysis problems, a given behavior can be predicted for specific function or characteristics. For example, given the diameter and length of a cylinder, the volume can be predicted using mathematical equations. The following examples further illustrate the analysis problems.

Example 2.1 For the circuit shown in Fig. 2.2, find how much current flow through the circuit 0.5 s after the switch is closed.

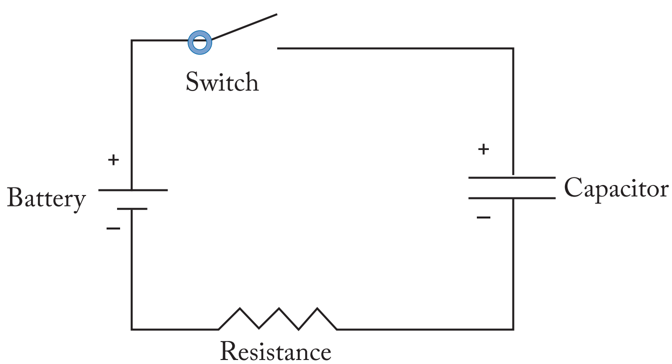


Figure 2.2: Example of an analysis problem—an electric circuit.

Example 2.2 Determine the deflection and maximum stresses for a simply supported beam given that the beam has a circular cross-section of diameter 2″and is loaded, as shown in Fig. 2.3.

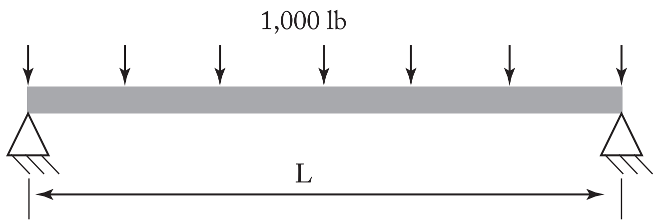


Figure 2.3: Example of an analysis problem—simply supported beam.

2.3 TYPES OF DESIGN PROBLEMS

Design problems can be thought of as a combination of any of the following sub-problems: (i) selection design; (ii) configuration design; (iii) parametric design; (iv) original design; and (v) redesign. In addition to the above types of design problems, robust design, sustainability and green design, and design from nature and art are also briefly presented.

Independent of the type of design problem, the more knowledge the designer obtains throughout the design journey, the various terms and language used in describing the product tend to decrease in the level of abstraction. That is, as time progresses and as more facts are known about the product or component, the semantic (verbal or textual representation of the component), graphical (drawing of the component), analytical (equations or procedures representing the component), and physical language (hardware or physical component) become more concrete in the information they provide to the designer. Various types of design problems are briefly described in the paragraphs below.

SELECTION DESIGN

Selection design involves the evaluation of potential solutions based upon the problem's need to make the right decision or choice. The potential solutions related to a specific component can be selected from vendor's catalogs that describe all the relevant characteristics of the component. The standard components include structural beams of various shapes and sizes, gears, valves, motors, pumps, springs, sensors, etc.

Consider an example where a design problem might be to select a tire for all terrain vehicles with a certain weight. The solution to this problem involves looking up tables or catalogs to select a specific tire, say A932004 based on weight restrictions and all-terrain ability, as shown in Fig. 2.4. There are a wide variety of components and systems readily available "off the shelf."

Figure 2.4: Tire Selection: A932004, A1016, and AR10317, respectively.

STRUCTURAL I BEAMS
ASTM A-36
Shape Designation (S)
Stock Lengths 20'

Metalworld, Inc.
1920 17th Street
Racine, WI 53403
(262)637-4407
www.metalworldinc.com

Nominal Size in Inches	Weight per Foot in Pounds	Thickness of Web in Inches	Width of Flange in Inches
3	5.7	.170	2.330
	7.5	.349	2.509
4	7.7	.193	2.663
	9.5	.326	2.796
5	10.0	.214	3.004
6	12.5	.232	3.332
	17.25	.465	3.565
7	15.3	.252	3.662
	20.0	.450	3.860
8	18.4	.271	4.001
	23.0	.441	4.171
10	25.4	.311	4.661
	35.0	.594	4.944
12	31.8	.350	5.000

Figure 2.5: Selection design of an I-Beam section to meet required specifications (source: www.metalworldinc.com).

Another example of a design problem might be to select an I-beam to support a central load of 100 N acting on a beam of length 3 m. The solution to this problem involves looking up tables or catalogs (see Fig. 2.5) to select a specific I-beam to meet the above needs. Again, there are many components and systems readily available "off the shelf."

CONFIGURATION DESIGN

In *configuration design*, the components are already designed. The question is how to assemble them into the finished product to improve performance and size (for example, packaging electro-mechanical components into a motor).

Consider an example where the objective is to design the location of a laptop in a backpack so that it is easy to carry. Figure 2.6 shows the possible backpack configurations to hold a laptop.

Figure 2.6: Configuration design for the location of laptop in a backpack.

Another example may be to design the location of a car engine in an automobile. Figure 2.7 shows the possible configurations: (a) engine behind driver, forward control, and driver ahead of front axle; (b) engine ahead of front axle, step-through control, and driver ahead of front axle; and (c) engine ahead of driver, convention control, and driver behind front axle.

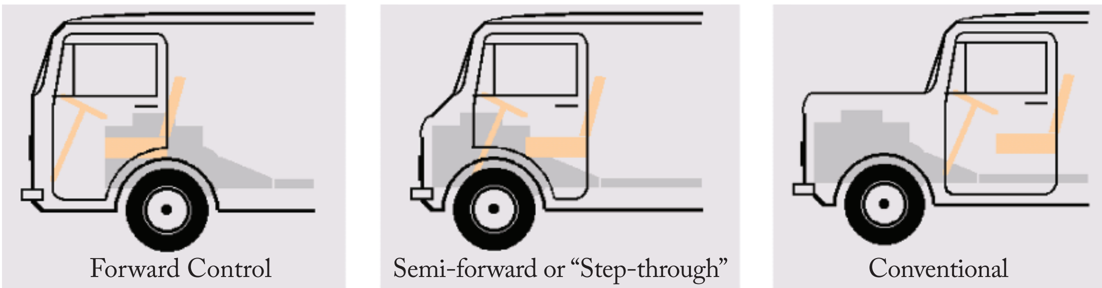


Figure 2.7: Configuration design for the location of an engine in a commercial automobile.

PARAMETRIC DESIGN

Parametric design involves discovering values for features (dimensions) or design parameters that characterize the design objectives. The design parameters (usually relate to specific sizes, material types, and manufacturing process requirements) and the performance may be expressed in equations through relationships. To develop a systematic parametric design, the following steps can be followed.

- Formulate the parametric design problem by identifying the design variables which influences the performance.
- Generate alternate designs by selecting different values for design variables.
- Analyze the performance of all of the alternate designs using analytical or experimental methods.
- Evaluate all of the alternate designs to determine the best design.
- Refine and optimize the design variables for feasibility and performance.

For example, consider designing a beverage can (approximated as a cylinder) with a radius (r) to hold a fluid volume of $V = 10\text{ cm}^3$. The volume (V) of a beverage can with radius "r" and length "l" can be determined by

$$V = \pi r^2 l.$$

Given $V = 10\text{ cm}^3$, the design problem reduces to finding values for "r" and "l" to satisfy the above equation. A variety of can shapes can be obtained by varying the diameter and length (with "r" and "l") to achieve the desired fluid volume for the beverage can.

ORIGINAL DESIGN

The creation of a process, assembly, or component not in existence or not available to the designer is an *original design*. There is no specific algorithm to come up with an original design, each design represents something new and unique.

REDESIGN

Finally, *redesign* is the modification of existing products to meet new requirements, attract new customers, or to implement new technologies. Most of the companies redesign an existing product to improve the performance, cost, additional functionality, or aesthetics. For example, the I-Phone was redesigned in the past couple of years, with new features that are very attractive to customers by changing the size, shape, configurations, and materials.

2.4 SOLVING DESIGN PROBLEMS – STRATEGIES

The products of engineering design are all around us, ranging from common household appliances such as toasters and lawn mowers to car seats, airplanes and canoes. These products as mentioned previously, arise out of customer and market demands, and are modified and refined as needed, to improve technical performance and customer satisfaction. In addition to customer need or marketing opportunity, there are other factors that have to be considered before a decision is made to address or tackle a design problem. These include such factors as time, cost, manpower, urgency, and necessity. While the first three factors are commonly noted and understood, it is important to pay attention to the latter factors as well. For example, consider a situation in which a customer complains of a particular brand of hair dryer that short-circuits frequently. This situation is both annoying and potentially dangerous to the customer, and calls for a necessary degree of urgency in solving the problem.

There may also be other situations, where a decision is made to defer/postpone action, or do nothing to address a problem. For example, automobile manufacturers design cars to have gas emission rates that are legally acceptable and choose to defer or delay other eco-friendly features that are not legally mandated. Finally, defects or flaws in a product may be so severe or catastrophic that the decision is made to recall and retire all of them (defective tires leading to sports utility vehicle rollovers, laptop computer batteries that become too hot with use and literally burn up the computer, etc.).

Depending on the nature and scope of the design problem, there are a number of strategies or approaches that may be used to solve the problem. These strategies are briefly summarized below using the hair dryer example mentioned above. Let us assume that a defect in a specific part of the dryer was identified as being mainly responsible for the short circuiting problem. What strategies can we use to tackle this design problem? The design problem strategies discussed in the previous section and also listed below will help you get started.

Parametric design or variant design strategy: In this approach, the solution to the design problem is focused on changing some parameters or dimensions of the part such as its thickness, length, or material.

Configuration design: This strategy focuses on changing the configuration (geometric features for example) of the part, and then observing its performance.

Selection design: In this strategy, it is assumed that the defective part is due to poor or improper fabrication, and, therefore, a similar part from a reputable vendor is selected and purchased, to take the place of the faulty part.

Redesign: Under this approach, the faulty part is removed from the particular subsection of the product in a re-design strategy.

Concept design strategy: The technical features that led the part to be defective are analyzed and the part is built again with new and improved technical properties.

Any combination of the above design strategies may be employed to address the hair dryer design problem. Another option not mentioned in the above list, is the do nothing option, where the solution may be to discontinue the product for safety reasons.

It is very important to remember that the selection and success of any particular design strategy lies in large part on the amount of information available regarding the nature and origin or roots of the design problem. For the simple example discussed above, where a defective part caused product failure, the solution strategies were self-evident and obvious. The solution strategies are rarely as clear cut or obvious when tackling design challenges and opportunities today. Moreover, time and cost expenditures limit the capacity of businesses to gather all the information related to figuring out the source of failure in a product. Therefore, design engineers play a key role in assisting business partners in formulating the design problem—getting the right information needed to select the initial design strategy solution. You will learn in Chapter 4 that design problem formulation is a very critical aspect of the design problem solution, and forms the basis or foundation for all the design strategies and approaches considered.

In addition to the design problem types discussed in Section 2.4, engineers should be aware of the following design methodologies as well.

2.5 ROBUST DESIGN

A "robust" product is one that functions as intended, regardless of variations in materials, processes, the environment, and the product's use or misuse. In traditional design, critical design parameters are determined without considering the variations (noise) coming from various sources. The tolerances to critical design parameters are added later, after the product is designed. In contrast, the robust design method estimates the design parameters and tolerances so that the product's performance is insensitive to noises or variations.

Figure 2.8 shows an overview of the robust design methodology. Robust design is conceptually easy to understand in that for a given performance target, there may be many combinations of parameters that will yield the desired result. But, some of these combinations are more sensitive than others. We would like to select the combination of parameters that are least sensitive to product performance in the presence of noise factors. The robust design process uses experiments and data analysis to identify a set of robust points for the design parameters we can control. Robust designs take into account these potential sources of variation and generate "new" design information that is often critical for improving product quality, reliability, performance, and cost.

The robust design method also called the Taguchi method is the most powerful method available for reducing product cost, lowering product development time, and maintaining customer satisfaction. A strategy called "Design of Experiments" (DOE) has been used effectively in robust designs to identify and experimentally control the impact of potential design factor parameters and noise (uncontrollable variability) factors on desired performance characteris-

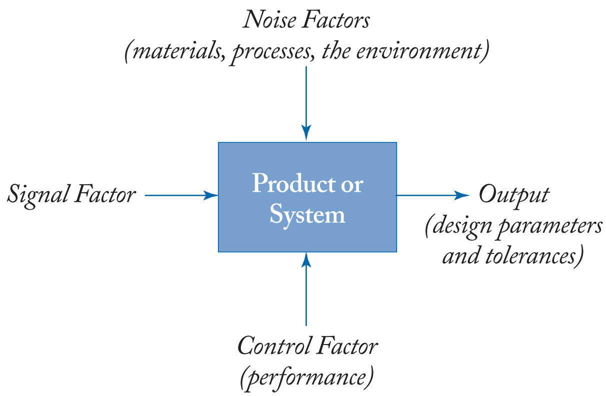


Figure 2.8: Overview of the robust design.

tics. This method has been successfully employed in various industries including automobiles, telecommunications, and computer software.

To develop a robust product through DOE, the following steps are followed.

- Identify input parameters (signal factors), noise factors, and output parameters related to performance.
- Formulate an objective function by minimizing output (performance metrics).
- Develop the experimental plan involving experimental designs (full factorial or fractional factorial or orthogonal array or one factor at a time).
- Run the experiment by testing the product under various conditions obtained from the experimental plan.
- Conduct the analysis by obtaining the mean and variance for the objective function.
- Select and confirm factor set points that have strongest effect on mean performance and variance, thereby achieving robust performance.
- Reflect and repeat to further optimize the product performance.

2.6 SUSTAINABILITY DESIGN

Sustainability is a global issue affecting many people on this planet. According to a United Nations report (1987), up to 70% of the Earth's land surface will be destroyed or disturbed over the next 25 years. Sustainability means "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Our Common Future, Oxford

University Press, 1987) [5]. Engineers must incorporate and adopt "sustainability" in all engineering products. Sustainable development includes three elements: environment (impact on nature and earth's environment), society (needs and quality of peoples lives and communities), and economy (cost related to infrastructure and business services), as shown in Fig. 2.9.

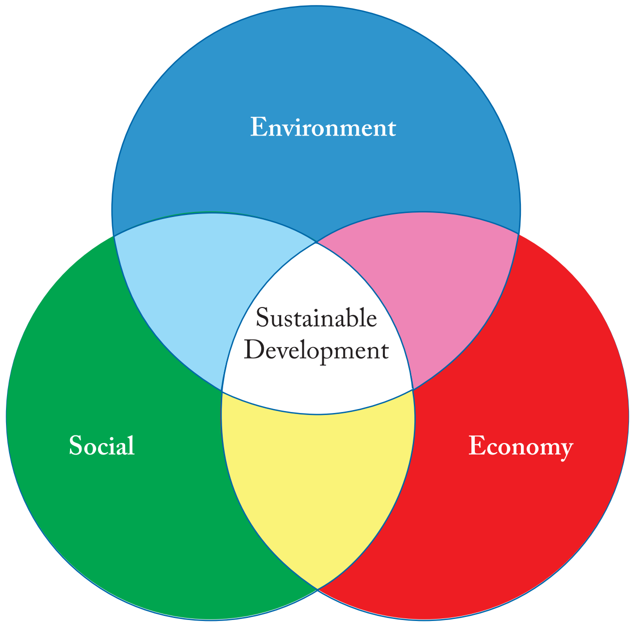


Figure 2.9: An overview of sustainable design/development.

Several challenges arise when dealing with sustainability. The goal of sustainable design is to produce products using only renewable resources. Environmental aspects therefore need to be incorporated into engineering designs in the same way as economics and safety and aesthetics. Due to increasing concerns about the environment, current and future product designs should address the issue of sustainability throughout the life cycle of the product by minimizing the usage of materials, labor, and other factors. For example, the design team may consider selecting materials for products that are environmentally friendly, biodegradable, and recyclable.

Figure 2.10 shows an example of recycling aluminum cans into usable products (sheathing, sandwich panels) for low-cost housing applications. A mobile coffee house designed by VCU students in Richmond Virginia for use in Monroe Park is shown in Fig. 2.11 to illustrate the history and sustainability aspects.

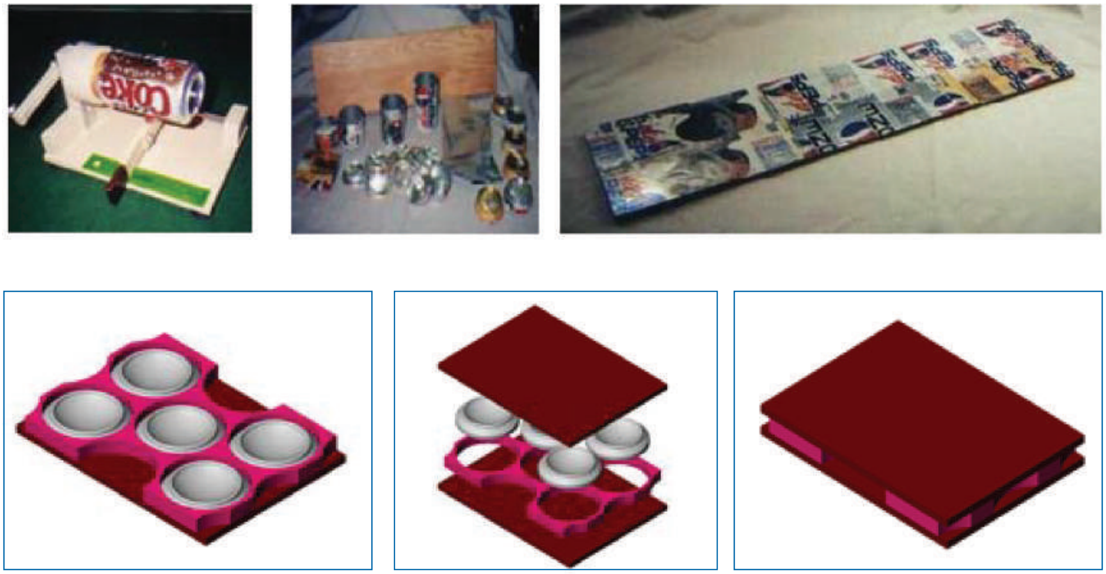


Figure 2.10: A schematic of production of composite panels from recycled beverage cans.

Figure 2.11: Design of a coffee house for use in Monroe Park at VCU.

2.7 NATURE-INSPIRED DESIGN

Multidisciplinary designs in engineering realize that 21st century innovations in engineering and biotechnology will involve "out of the box" ideas. Living systems that evolved over thousands of years, integrate design at multiple size scales. Inspiration for engineering design can come from many sources. The best source of inspiration may be Nature's design of many living systems (see Fig. 2.12).

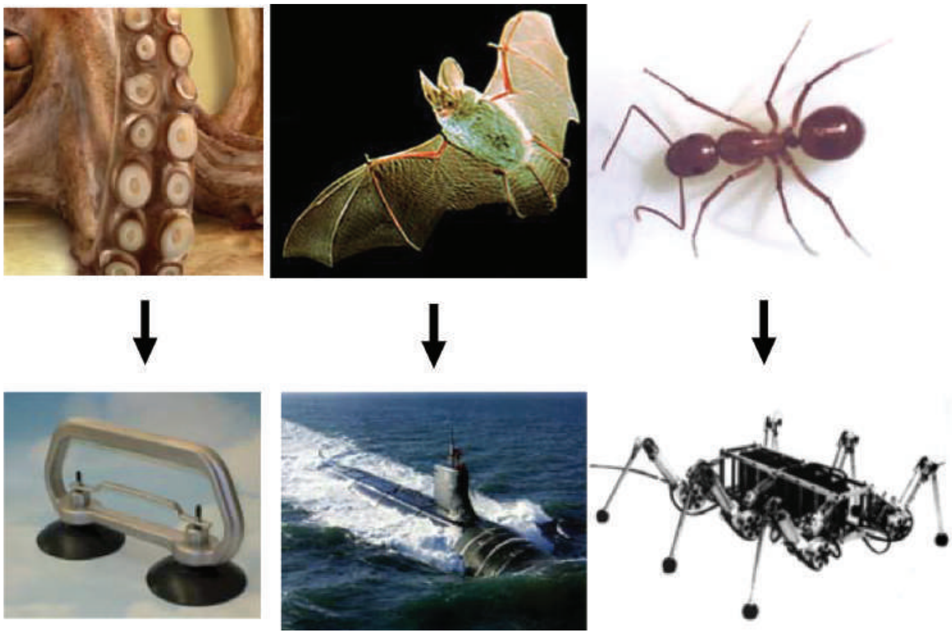


Figure 2.12: Nature inspired design (images courtesy of www.morningsun.net, https://suctioncups.com, https://uanews.org, https://olypen.com, www.navy.mil, pkmet.szm.sk).

For product design, inspiration comes obviously from other products, and from new materials and processes. The mechanics of plants/animals—the things they can do, and the way they do them continues to mystify, enlighten, and inspire designs of the 21st century. Some of the innovative products inspired by nature include suction cups (octopus), smart robots (insects and bugs), and sonar devices (fish or bat echolocation). Researching designs that mimic nature will help to foster new design concepts for future products and technologies.

Nature is filled with beautiful and wonderful creatures and creations that continue to inspire and inform us everyday. Yahya (2007) [26] presents examples of many man-made inventions that were inspired by nature including the following: scuba diving gear based on the shape of the fins of whales, hiking boots and shoes based on the hoofs of mountain goats, submarines structure and coating similar to that of a dolphin, and Velcro bandages that were modeled after burrs. Insects such as ants, chitins, and scorpions have been the basis for many new robotic technologies. Figure 2.13 shows some of the innovative designs inspired from biology.

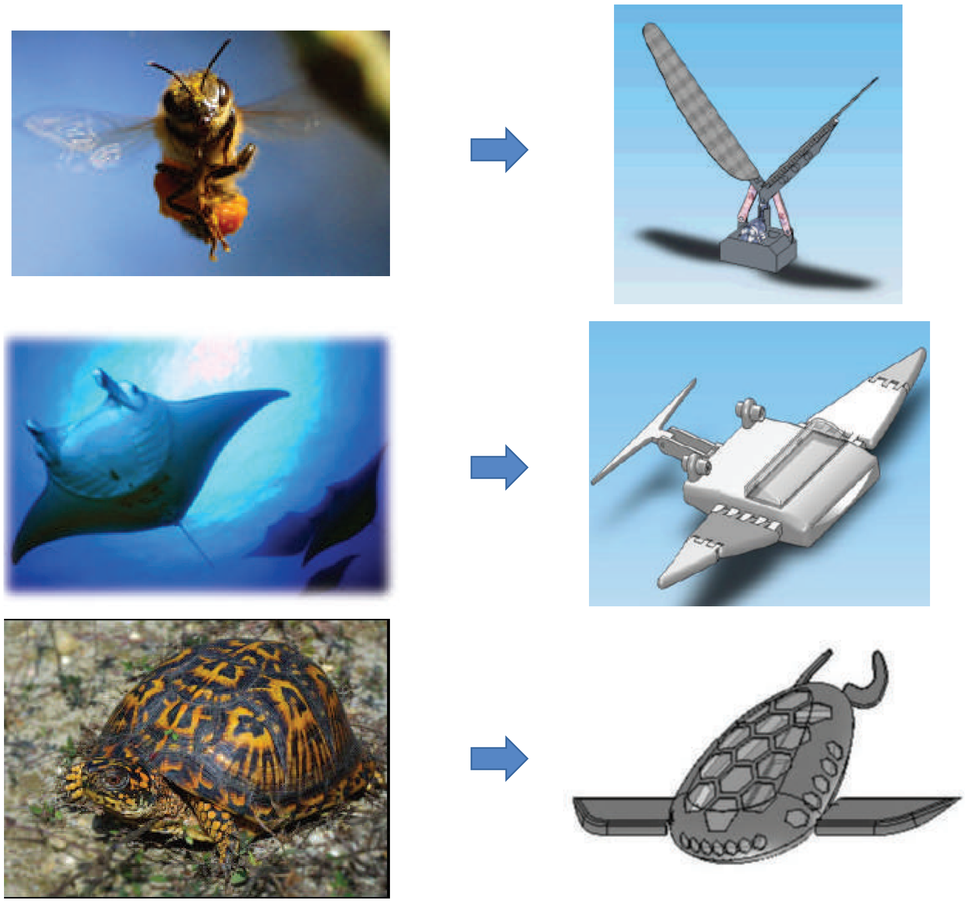


Figure 2.13: Examples of bio-inspired (left) and engineering design concepts (right).

2.8 INTEGRATION OF ARTS, NATURE, AND DESIGN FOR INNOVATION

Design innovation can be achieved through the integration of arts and engineering design principles and by exploring the creative methods and processes existing in the arts community as well as taking inspiration from nature, as shown in Fig. 2.14.

Let's ask a question, who is an engineer? Most people will tell you that engineers are designers, scientists, inventors, and innovators. Few will say that an engineer is an artist. Engineers'

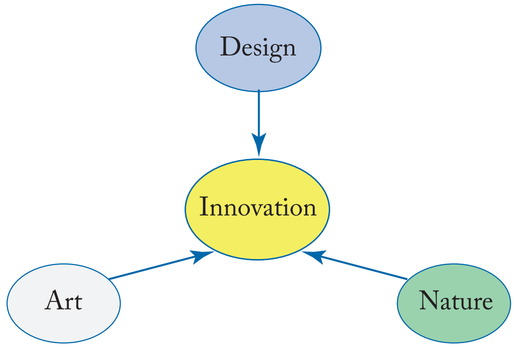


Figure 2.14: Design innovation is the synergy of art, design, and nature.

artistic side is clearly evident in their work. For example, Robert Fulton, steamboat inventor, and Samuel Morse, inventor of the Morse code and the telegraph, both pursued careers in art before changing their interests to technology. Architects, also engineers, make many detailed sketches of their final design product before beginning construction. The bridge-builder Robert Maillart is known for his use of "structural art," a construction style that started during the industrial revolution.

Leonardo da Vinci, best known for his famous painting, the Mona Lisa, was also a very capable engineer. In the late 1400s, he began working on several ideas for human powered flight. It was his background in art that provided him the creativity to visualize such revolutionary designs that were far ahead of their time. In his paintings and drawings, one can observe the attributes associated with artwork, specifically symmetry, balance, and rhythm. In one example, we can see that the wing he has designed and drawn is symmetric in that it is a mirror of itself if it was split down the middle. There is also a natural balance and rhythm to the drawings, where the weight of the man is balanced by the lifting power of the wing through its rhythmic movement. By studying the drawings we can almost imagine how the apparatus would look if it were put into motion. In many ways his designs transcend and/or combine the elements of art, nature, and design.

Engineering design is at its best when it integrates the aspirations of art, science, and culture. Think back to a time when you stopped to admire a painting, building, or sculpture. It is very likely that features such as its color, shape, appearance, etc. and the feelings they evoked in you are what attracted you to the work. Functionality was probably not the first thing that you thought about. Many architectural and natural wonders of the world are highly regarded and endure today because of both artistic/aesthetic appeal, as well as sound engineering design. A good concrete example can be found in the Pyramids of Egypt in Giza. The harmonious marriage of art and design can be found in many other examples such as Europe's gothic cathedrals, and India's Taj Mahal to mention a few. These monuments would not last as long they have without sound engineering design, and at the same time, not cherished as they are without the artistic appeal.

Developments in technology and the streamlining of manufacturing processes over the past couple of decades have transformed the U.S. economy into a commodity economy. There is only one factor that differentiates one competing product from on another: *design*. Companies such as Ford, Tesla, Apple, Amazon, and Samsung are pioneers in positioning design as a key contributor to innovation. These creative companies, along with others, are emphasizing the role of design in connecting with customers' emotions and needs, and constructing maps that show the path to innovation. Engineering design is a passion, and it is a process of invention that allows us to develop new devices, tools, materials, and procedures to meet needs that are not met by existing technologies.

To illustrate how art can be integrated into engineering, a design project was initiated by the author involving both engineering and arts students working together to come up with an exhibit to display in a zoo setting. The design exhibit is presented in Fig. 2.15 and shows that Rhinos see from the sides unlike humans who see directly.

Figure 2.15: Rhinos (left) and zoo exhibit design mimicking rhino's head (right).

There are differences in problem solving methodologies and projected consumer use between engineering and arts, which are presented in Tables 2.1 and 2.2.

Table 2.1: Differences in problem solving methodologies

Engineering	Arts
Knowledge based on hard science principles	Knowledge based on standards of visual perception
Mathematics, physical, and chemical sciences	Shadow, form, line, compositions, etc.
More formulaic approach to problem solving	No standard approach to problem solving

Table 2.2: Differences in projected consumer use

Engineering	Arts
Consumer asks for a funcitonal product that meets a need	Audiences expect to have sensibilities engaged
Expects longer product life	Expects to understand or appreciate artists creative vision
Safety designed into product	Understands object not in terms of usability, but in comprehension
No bias in product function	Expect art to exist within artistic context

2.9 EXERCISES

2.1. What are the various types of design problems?

2.2. Discuss the differences between analysis and design problems.

2.3. Design a gauge to measure the temperature range from 30–70°C.

2.4. You are a designer of vaulting polls. A simple model of vaulting poll is a cantilever beam. Design a new poll so that a 150 lb man deflects the poll by 4″when vaulting at one end. Design five configurations by parametrically varying the length, material, and diameter of the poll.

2.5. How would you design a laptop for easy travel that has several important accessories?

2.6. Identify a basic problem solving method for the following:

- **(a)** Finding a tool in a hardware store
- **(b)** Selecting new clothes for a birthday
- **(c)** Installing a wall-mounted speaker
- **(d)** Selecting a new vehicle

2.7. Define robust design and comment on the issues that needs to be considered for an automotive control system.

2.8. Define sustainability design and the implications for the environment.

2.9. Develop ideas using nature as a teacher for designing a sensor to measure pressure in the range of 10–100 MPa.

2.10. Design a toy for boys and girls that is inspired from nature.

CHAPTER 3
Reverse Engineering

After reading this chapter, you will be able to:

- Define reverse engineering
- Explain the rationale for taking something apart
- Dissect a product
- Create a component decomposition diagram

3.1 OVERVIEW

This chapter discusses reverse engineering or product dissection and outlines reasons for dissecting a product. The process of product dissection and completing the component decomposition diagram is explained. Through reverse engineering, students gain insights into product redesign methods.

3.2 REVERSE ENGINEERING

Reverse engineering is the process of redesigning an existing product. A product can be defined as something that a customer purchased and use it as a unit. Examples of products include an electric drill for the workshop, a can opener in the kitchen, or a new car (like the car industry, when designing 2011 model, it is time to start on the 2012 model) that are being used after they purchased. For engineering and technology students, an example of reverse engineering may be looking at the previous design process that the team just finished redesigning. Reverse engineering looks at what was done right, what is needed to be designed that was left out due to various reasons as a result of new government standards or availability of better materials or manufacturing technology, or customer needs.

3.3 REASONS FOR DISSECTION

Why take something apart? Reasons for taking things apart could be curiosity as to how something works; the desire to fix something that is broken; or to learn from engineering successes and failures. Further, one may also be interested to see how something is made so that the design can be documented to duplicated (reverse engineering) or improve on the design (value engineering) for benchmarking, or competitive analysis. Also, it is possible to compare different design alternatives, estimate costs, or evaluate the competition and learn to see how each component performs in the product and how to improve the design. All of the above reasons necessitate dissecting a product or assembly as a prelude to reverse engineering.

3.4 PRODUCT DISSECTION

Products can be simple (a few components) or complex (a thousand components) as shown in Table 3.1, depending on the number of components and their size and function. For example, a

Table 3.1: Examples of simple and complex products

Simple Products	Complex Products
	
	
	
	
	

mechanical pencil consists of 4–5 components. In contrast, an automobile or an airplane contains hundreds to thousands of components. Products usually consist of parts (single piece) or assemblies (more than two pieces assembled in some fashion). Examples of standard parts include pin, nut, bolt, rivet, gear, and so on, whereas assemblies include pumps, motors, switches, brakes, engines, etc. In general, some assemblies are standard while others may be custom (special purpose parts/assemblies). Special purpose parts are those that would need to be manufactured for a specific product.

Usually, the dissection begins by dividing the product into assemblies according to their function. These will be recorded on the component decomposition diagram, similar to a family tree with many branches. The component decomposition diagram categorizes the components into an assembly and subassembly with all of the individual components under each subassembly. Then, components of the subassemblies of each assembly are listed. A record is made as to whether they are standard parts or special purpose parts by subassembly. While dissecting the product, the parts are laid out in order that they can be cataloged as to the assembly or subassembly by function. The function of each component and how it works or relates with the other components is determined.

Clues as to the use of the components can come from the material that they are made of, for example metal, plastic, or fabric. What other components do they come in contact with? Are they of the same material or different materials like when plastic comes in contact with brass or aluminum? The physical characteristics of the component can lead to a better understanding of its functions and how it interacts with the other components it comes in contact with. For example, consider the threaded component. What type of either national fine or national coarse or metric should be used? Recording the dimensions can assist if further research of compatible components is needed for product development. Product dissection can also provide a size perspective when presenting the findings.

3.5 PRODUCT DISSECTION – EXAMPLES

The following are examples of product dissections with their component decomposition diagrams. The first product is a Do It Best Adjustable Utility Knife shown in Figure 3.1. The Do it Best Retractable Utility Knife is an example of heavy duty construction. It features a heavy two-piece die-cast body. The body has ribs to assist with the gripping of the knife and help prevent slipping. The blade has three different positions so that the user may choose the amount of blade exposed and the depth of the cut. Three extra blades are included and are stored inside the utility knife.

The dissected utility knife consisting of ten components, four of which are razor blades stacked together (component 7) is shown in Fig. 3.2. Component 7 is recorded as one item with four pieces.

The component decomposition diagram for this product breaks down into three assembly or systems (housing, razor blade holder, and cutting tool) according to function. The housing is

Figure 3.1: Do it Best Adjustable Utility Knife (courtesy of James Earwood).

1 Left housing
2 Right housing
3 Screw, pan head
4 Holder, razor blade
5 Adjusting button
6 Spring
7 Razor blades (4)

Figure 3.2: Do it Best Adjustable Utility Knife dissected showing various components (courtesy of James Earwood).

made up of three components: the left housing, the right housing, and a pan head screw. The diagram also identifies whether the component is special purpose or a standard part that could be purchased. The second assembly is the blade holder. It too is made of three components: the holder, the adjustment button, and the spring. Again the components are identified as special purpose or standard parts. The last assembly is the blades, four each, and they are standard parts.

Another example is a Boston two-hole punch, as shown in Fig. 3.4. The dissected components (see Fig. 3.5) and component decomposition diagram are also presented in Fig. 3.6.

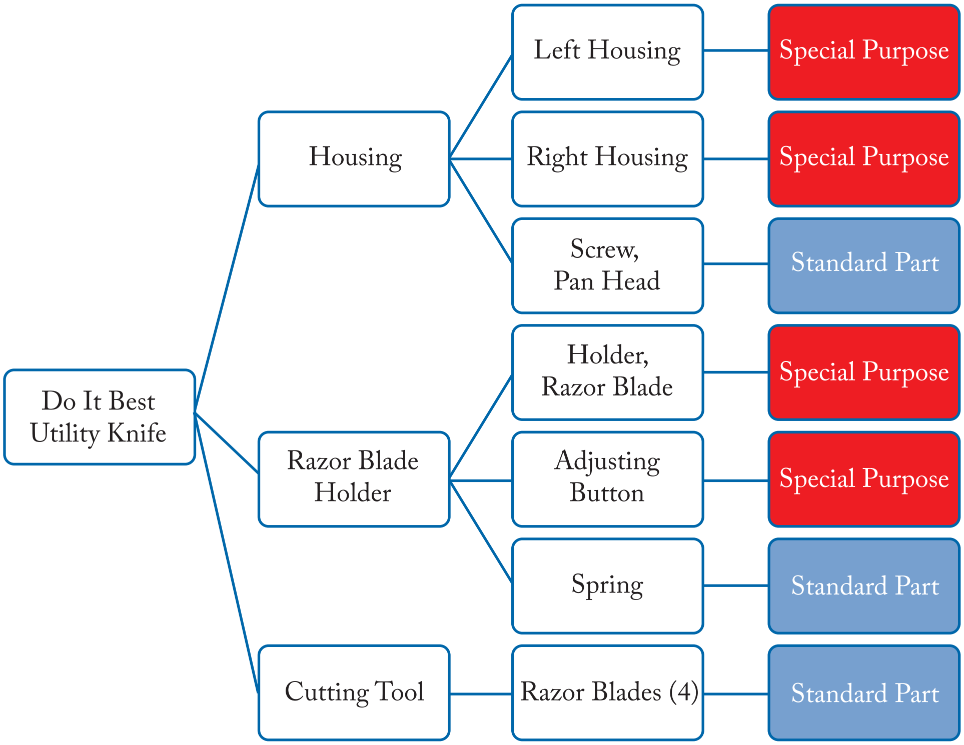
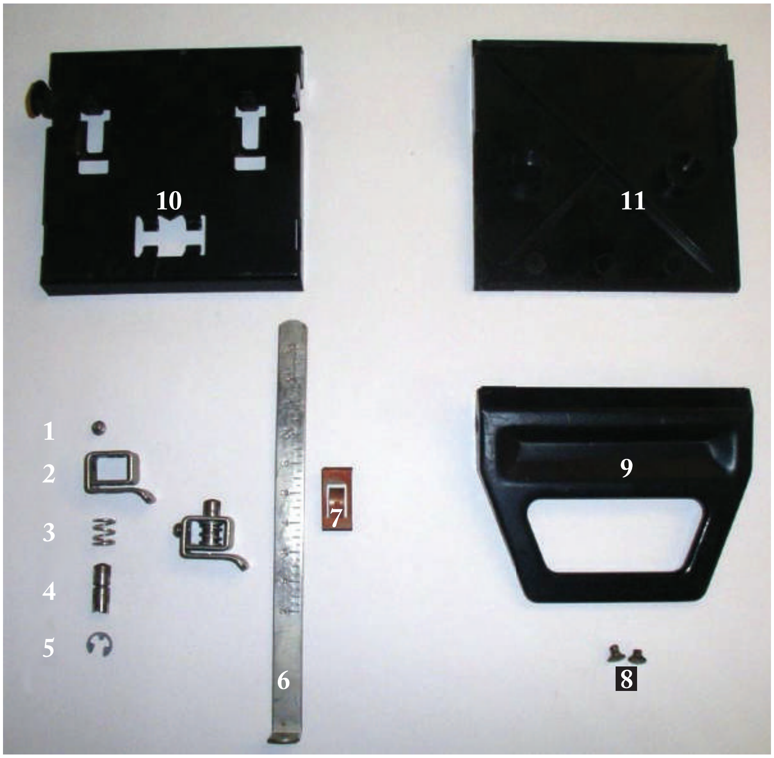


Figure 3.3: Adjustable utility knife—component decomposition diagram.

Figure 3.4: Product dissection example: Boston two-hole punch (courtesy of James Earwood).



Boston 2-Hole Punch

1	Screw (2)
2	Bracket, hole punch (2)
3	Spring (2)
4	Punch, hole (2)
5	Clip, E, retaining (2)
6	Guide, paper width
7	Clip, retaining, guide
8	Rivet (2)
9	Handle/lever
10	Base
11	Cover, paper hole catch

Figure 3.5: Boston two-hole punch: dissected components (courtesy of James Earwood).

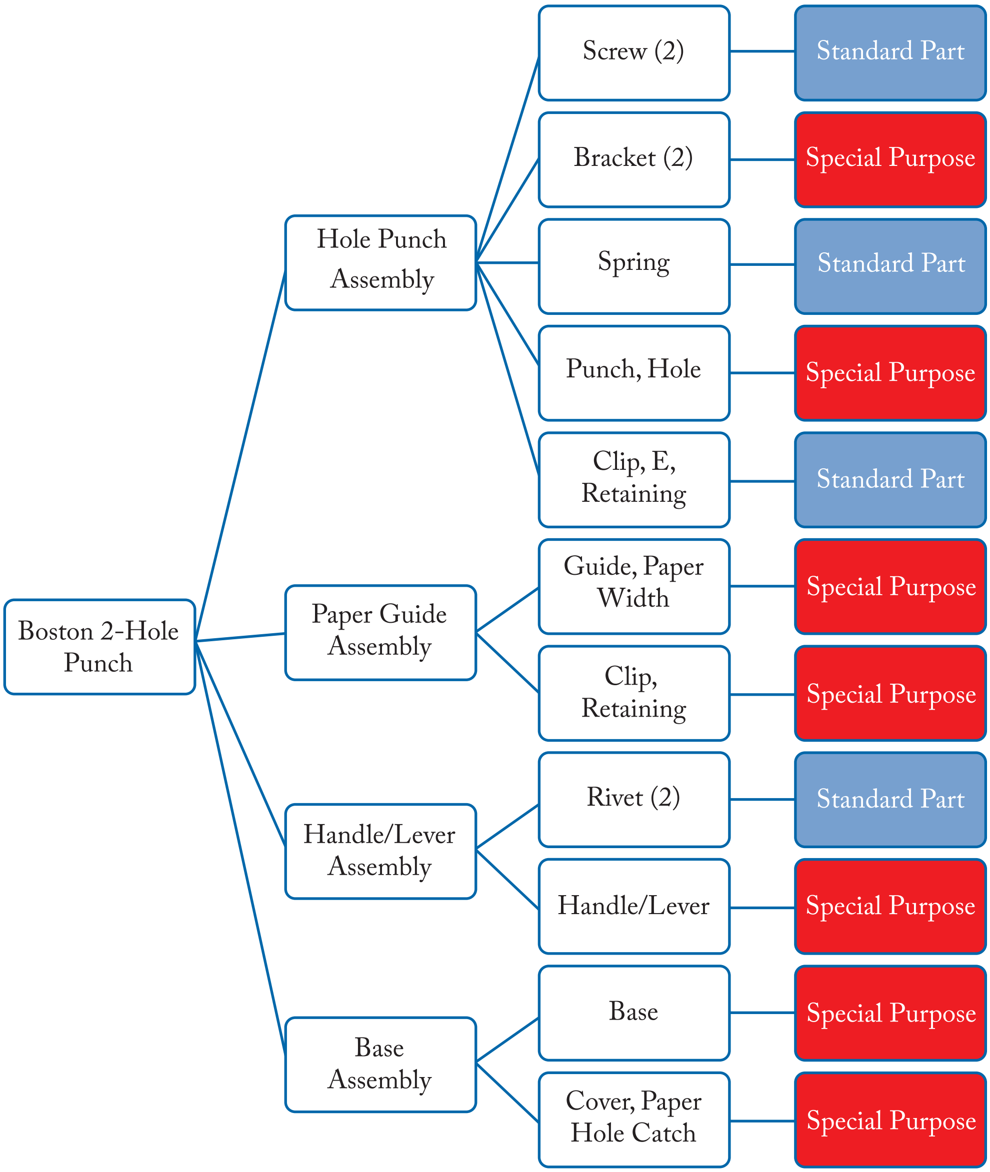


Figure 3.6: Component decomposition diagram for Boston two-hole punch example.

3.6 SUMMARY

Reverse engineering is the process of disassembly, examination, recording, and analyzing how a product functions. This is done for a variety of reasons with the focus on obtaining a better understanding of how a product functions, and why the customer likes or dislikes the features examined. It is a small part in the product redesign process. A typical product dissection sheet shown in Fig. 3.7 is used during the product dissection assignment/activity.

Product Dissection Data Sheet

Manufacturer/Model Number: **General Product Information:**

How many detachable pieces does the product have? ______

Part number: Part name:

__________ ______________________________________
__________ ______________________________________
__________ ______________________________________
__________ ______________________________________
__________ ______________________________________
__________ ______________________________________

Describe the pieces including their functions and their materials.

Part number: Material & Functional Description:

__________ ______________________________________

__________ ______________________________________

__________ ______________________________________

__________ ______________________________________

__________ ______________________________________

Is it easy to detach each part?

Part number: Detachment (Easy, difficult, use of force etc.):

__________ ______________________________________
__________ ______________________________________
__________ ______________________________________
__________ ______________________________________
__________ ______________________________________
__________ ______________________________________

Describe the packaging. Is it easily opened? Describe the opening procedure.

Remarks:

Figure 3.7: Product dissection data sheet.

3.7 EXERCISES

3.1. Explain reverse engineering.

3.2. List five reasons for dissecting a product.

3.3. Find a kitchen product, dissect it, and complete a component decomposition diagram.

3.4. Find a product in the garage/workshop or tool box. Dissect the product, complete the component decomposition diagram, and write a report of how your team disassembled, examined, recorded, and reassembled the product to working condition.

CHAPTER 4

Design Requirements

After reading this chapter, you will be able to:

- List the steps in the design journey process
- Gather information to develop requirements for a design need
- Develop a project schedule utilizing tools such as the Gantt chart
- Understand and develop design specifications using QFD technique
- Write a design project proposal

4.1 OVERVIEW

The design journey process is a systematic methodology for solving design problems. This chapter introduces the methodology of the design journey process with examples. In this chapter, there is more emphasis on the early steps of the design journey process, specifically gathering design requirements and project planning. The techniques are explained and illustrated, with examples as needed, to facilitate real-world implementation. Specific tools discussed in this chapter include project scope, design brief, Gantt chart, and QFD technique. Several examples of QFD are presented.

4.2 DESIGN JOURNEY PROCESS

Design innovation involves designing a new product or service that substantially improves the functional characteristics as well as affordability. From computer chips to space vehicles, engineering design principles and processes are vital to creating products and services needed by mankind. Whether the design task relates to creating medical devices, smart robots, Micro Electro-Mechanical System (MEMS) devices, heating and cooling systems, or racecar engines, the basic engineering design process remains the same. The design journey process is essentially a process of problem solving—coming up with the best match or solution to an identified problem or need in society.

The transformation of an ill-defined problem into a complete functioning product (as shown in Fig. 4.1) requires the following stages: establishing a need, developing a plan (how to solve the problem), understanding the problem, developing requirements and comparing to existing solutions, generating and evaluating additional concepts, deciding or choosing a final solution, and communicating the results. The goal of the design process is to find the best possible solution to an ill-defined problem that leads to a quality product with the least commitment to time and other resources through the organization and management of people and information. The reason we study design methodologies is to learn from previous examples, to understand the effectiveness or lack thereof of different methods, and avoid repeating the mistakes of others. The design process is successfully accomplished through consistent communication among the members of the design team.

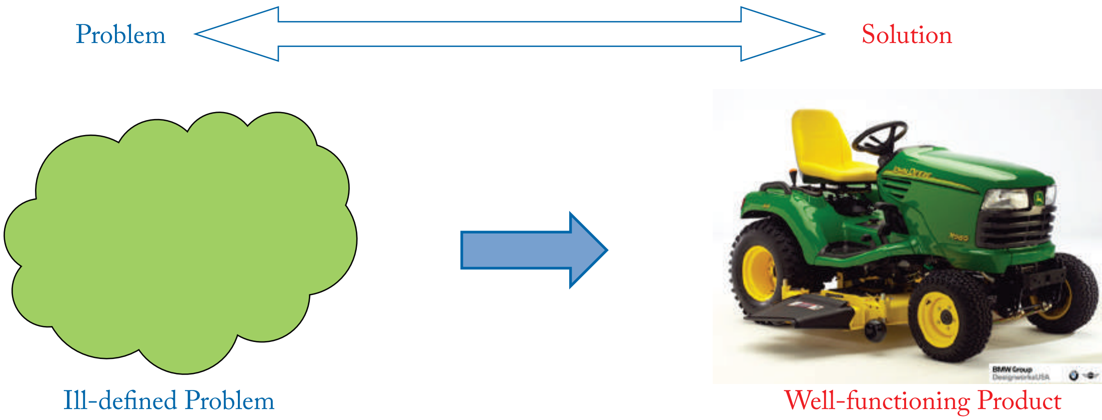


Figure 4.1: Design journey is a process to find a solution to an ill-defined problem.

The following section provides an overview of the product design process. The design process is a sequence of steps that helps define various aspects of the design in a systematic manner, as shown in Fig. 4.2. Several steps underline the design journey process and are discussed further in this section.

It is worth mentioning that design is an iterative process going through design journey steps. The objective of following a systematic design journey process is to minimize the number of iterations required in order to generate a quality product. Designing quality into a product means designing a product that is easy to assemble, durable, and that meets performance criteria. The quality is integrated into the product through the design journey process by checking the technical documentation, dimensions, material properties, surface quality, and other factors that are critical for the form and function of the product.

4.3 DESIGN JOURNEY STEPS

The various steps in the design journey process are presented in Fig. 4.2. Below is a brief description and explanation of each of the steps in the design journey process.

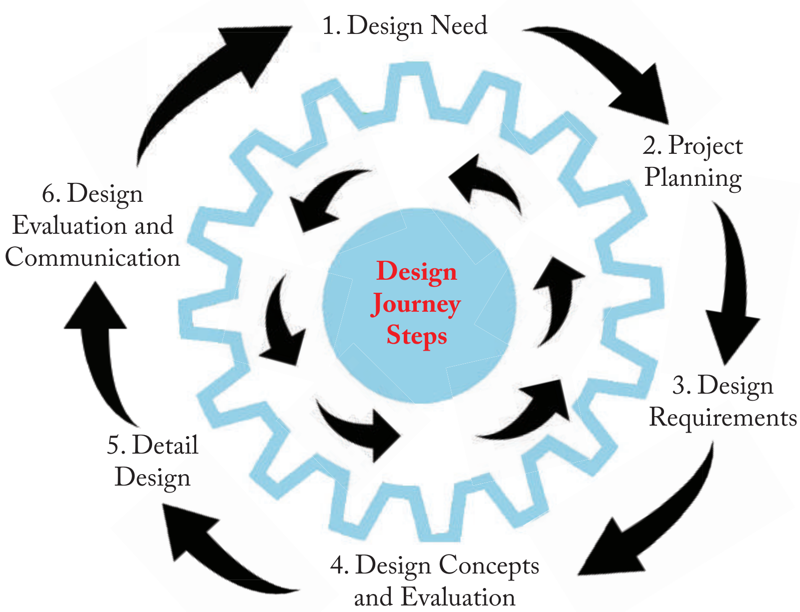


Figure 4.2: Steps in the design journey process.

STEP #1: DESIGN NEED

Identifying a societal need and defining the need in measurable terms is not as easy as it may seem. Needs may be market-driven, or may come from private industry or the introduction of new technology. They may also arise out of a need for improving an existing product or are a part of a larger project (space vehicle or race car) to achieve sustainability or even arise from federal regulations or national research initiatives. In general, there are several aspects that provide the design need, as discussed in the following.

Market Research: Several aspects are examined that include demographics (Who uses? Who buys?), socio-economic and cultural factors, sustainability factors, aesthetic parameters, and applicable technologies.

Existing Designs: This includes looking into reverse engineering the designs from functional performance, mechanical features, materials, manufacturing processes, and aesthetics perspectives.

End Users: This includes looking into how the end users are using the design through observations of physical interaction, psychological aspects, and how they are using/misusing the design/product.

Human Factors: This includes looking into how ergonomics (physical interface, tactile feedback, and user interface) and intuition facilitate using the design for communicating the function, design graphics, arts, visuals, and icons and their appeal to the end user.

Design Integration: This includes looking into how various electrical, mechanical, materials, and manufacturing requirements are integrated in an interdisciplinary fashion to achieve the required design.

Figure 4.3 shows some of the sources from which the design need can be generated. For example, the automobile industry is currently researching and producing hybrid/electric cars due to the positive response from consumers to the higher gas mileage and eco-friendly aspects of these cars. Pharmaceutical companies are always on the lookout for biomechanical devices that more effectively deliver medicines with fewer side effects. The National Aeronautics and Space Administration (NASA) successfully launched an unmanned space flight to Mars/Moon, charting new frontiers for space exploration with robots. It is the primary task of the designer to communicate closely with the clients and end users to fully understand the need, and assist the clients in creating a product or service that most closely meets that need. Clients, stakeholders, users, and designers typically work together in teams to define and carry out design-related projects.

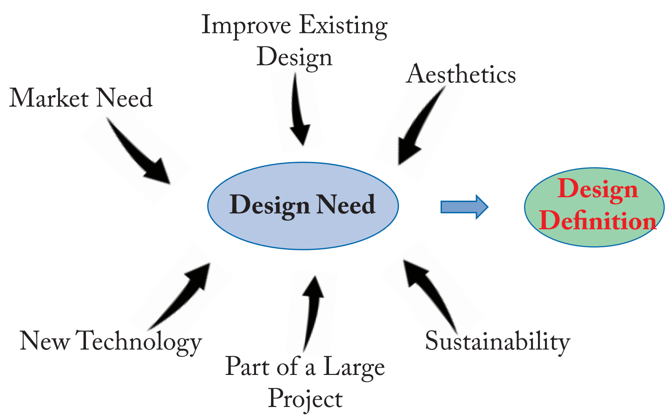


Figure 4.3: Generation of design definition from multiple perspectives.

Most design problems are not well defined and are open ended. The design project statement may not give all the information needed to find the solution. Identifying the missing information will be the key to fully understanding what needs to be designed. The goal in product design is to find the best solution that leads to a quality product with minimal cost and limited resources.

> "The mere formulation of a problem is far more often essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle require creative imagination and marks real advances in science."
>
> **Albert Einstein**

DESIGN NEED – GATHERING INFORMATION

During the design need identification step, the designer has to identify customer/stakeholder needs, which in itself is a process. The following are the three methods commonly used to gather information to determine customer/stakeholder requirements.

- *Observations:* This method involves observing customers using the existing product in order to see whether the product needs to be redesigned or develop a new design with improved properties and performance that would compete with the products already available in the market. Many requirements can be found by observing customers using the product since most new products are refinements of existing products.

- *Surveys:* The survey method is generally used to gather specific information or ask people's opinions about a well-defined subject. Surveys make use of questionnaires that are carefully designed and applied through the mail, over the telephone, or in face-to-face interviews. They are well-suited for collecting requirements on products to be redesigned or on new, well-understood product domains.

- *Focus groups:* These are used to capture customer requirements from a carefully sampled group of potential customers. This technique is best suited for developing original products or to gather the customers' views on product/design improvement.

DESIGN BRIEF OR NEED STATEMENT

A well-constructed design brief clarifies the project/design scope involving stakeholders and provides a clear description of the design need. This design brief is the first document that designers/engineers develop and inform all identified stakeholders. As the understanding of the design problem evolves, changes can be made and the design brief may be updated as the project moved ahead in the design journey process. A typical design brief includes the following information.

- What are the problem description and its objectives?

- What is the focus within/outside of the scope of the project?

- Who are the target users and the stakeholders that need the design?
- What are the constraints, assumptions, and standards that need to be considered?
- What are the key exploratory questions that need to be answered for various stakeholders through research, literature, and benchmarking?
- What are the expected outcomes and innovations?

STEP #2: PROJECT PLANNING

The project planning step of the design journey process includes developing a plan for the design process with respect to scope and resources available at hand to accomplish the design activities of the problem identified in step #1. There are various reasons for project planning, including obtaining better understanding the project objectives, eliminating the uncertainty and improving the efficiency of operations, and providing/guiding the project teams and minimizing the risk for project completion.

The resources may be categorized in terms of time, money, people, and manufacturing and testing capabilities. The main activities in the project/design planning step are:

- Form a design team
- Develop tasks
- Research the market
- Estimate schedule and cost

The following are the project planning steps in a design journey.

1. Design Team: The size of the design team depends on the specific project. It may be necessary that in a design team one person may have several titles or several people may have one title or perform different roles.
2. Identify the tasks and objectives and develop a sequence: The specific tasks/activities that need to be accomplished in the design project are identified. For each of the identified tasks, the objectives should be clearly stated, along with the anticipated outcome for that task. Each task objective should be defined in terms of information (developed or refined and communicated to others in terms of deliverables—drawings, design information, test results, etc.), that is easily understandable (by all team members) and feasible (with available personnel, equipment, and time). For example, a bar chart may be used to develop a sequence of the tasks that must be completed before, after, or in parallel, depending on the nature of the tasks involved in the design project.

3. Research the market: In this step, the focus is on gathering information—information on what is already available in the market, and information on assessing the competition. Resources such as trade journals, U.S. patents, and research reports are commonly consulted.

4. Estimate the design personnel and time and product development costs: Once a project plan is developed, the design team can estimate the product development cost. For each task, it is necessary to identify who on the design team will be responsible for meeting the objectives, what percentage of their time will be required, and over what period of time they will be needed. For each person assigned to a task, it is necessary to estimate not only the total time requirement but also the distribution of this time (ex. number of hours/week to be spent on the task).

PROJECT MANAGEMENT – GANTT CHART

Generally, a project plan is developed to meet the project deadline and manage various tasks involved in the design project. Gantt charts are used to represent the timing of various tasks planned in the design project. The horizontal axis shows the timeline and the vertical axis shows various tasks to be completed. The start and end of a task is usually represented by a horizontal bar. If the task is completed, then it is represented by a completely filled bar. The unfilled bars represent the fraction of the task that is completed.

An overview of a Gantt chart displaying various tasks and their timelines in the design process is shown in Fig. 4.4. A main problem with the Gantt chart is that it does not explicitly display the dependencies among various tasks. The dependencies dictate which tasks must be completed before others can begin or finish, and which tasks can be completed in parallel. When two tasks overlap in a Gantt chart it means they may be sequential, parallel, or coupled. In addition to Gantt charts, Program Evaluation and Review Technique (PERT) charts can also be used to represent both dependencies and timing of various tasks in the Gantt chart and estimate the "critical path," namely, identifying the longest chain of dependent tasks/events.

Commercial software such as Microsoft Project Manager is readily available for developing Gantt charts and managing design projects.

STEP #3: DESIGN REQUIREMENTS

In order to develop the best possible design, it is essential to develop a good understanding of the design problem and generate a set of design criteria/engineering specifications. Misunderstanding a design problem may result in bad design, higher cost, and delay in time to market. Therefore, it is very important to understand the design problem first before searching for any possible solutions. The goal in understanding the design problem is to translate customer needs into engineering specifications with specific target values. This is accomplished through the adoption of a technique known as Quality Function Deployment (QFD), as shown in Fig. 4.5.

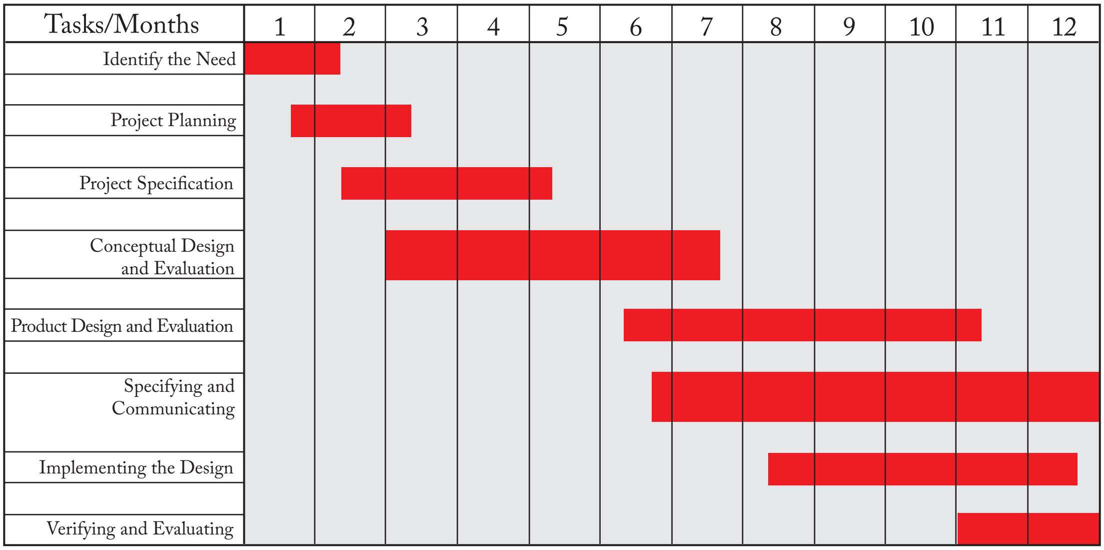


Figure 4.4: Overview of a Gantt chart showing various tasks and their timeline.

Figure 4.5: Translation of customer requirements into engineering requirements through the QFD process.

The QFD technique was developed in Japan in the mid-1970's, and has been utilized in the U.S. industry since the late 1980's. The benefits of applying the QFD technique include achieving a greater understanding of the design problem which results in higher-quality products with reduced cost and with quicker product development time. The QFD technique can be applied to the entire design problem or sub-problems. The Toyota Car Company was able to reduce the cost of a new car to the market by 60%, and the time to market by more than 30%, by using the QFD technique.

The following points further illustrate the importance of applying the QFD technique. The design team should employ the QFD technique even though they think they understand the design problem. The team must translate customer requirements into measurable targets, and worry about what needs to be designed rather than how the design will work and look. The QFD technique helps the design team to generate valuable information necessary for understanding the design problem including:

- The specifications or goals for the design/product
- How the competition meets the goals
- What is important from the customers' viewpoint
- Work toward certain engineering (measurable) targets

QFD TECHNIQUE

The development of design specifications (customer and engineering requirements) is accomplished through the use of the QFD technique. The overall QFD process for developing specifications for a design project is presented in Fig. 4.6. Each of the steps in the QFD technique is shown in each block in Fig. 4.6. Applying the QFD steps builds the house of quality describing Who vs. What; What vs. How; Now vs. What; and How vs. How? Also, the QFD technique forms the foundation for the concept generation phase of the design process.

The seven steps in the QFD technique are summarized below.

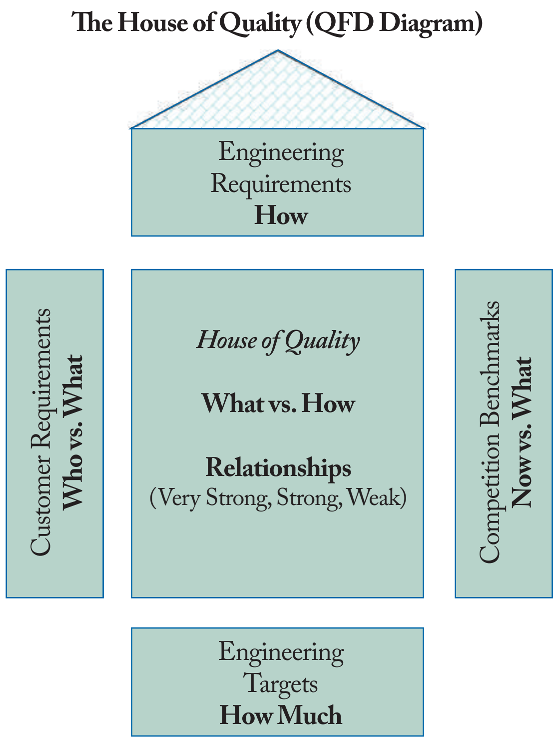


Figure 4.6: Overview of the QFD technique for design specification development.

1. Identification of customers—"Who" in the House of Quality. The customers may include several personnel including consumer/user, stakeholders, designer, management, manufacturing, sales, service, and standard organizations (Product Standard Index, ASME, American National Standards Institute, American Society for Testing of Materials, Underwriters Labs).

2. Customer requirements determination—"What" in the House of Quality. In this step, the designer needs to determine what is to be designed from the customer wants. Table 4.1 illustrates the features customers (consumer, production customer, and market/sales customer) typically want in a design/product. All of the wants should be considered in the design problem.

Customer Requirements
Who vs. What

Table 4.1: Customer "wants" in a design/product

Consumer	Production Customer	Marketing/Sales Customer
• Lasts long time • Works as it should • Easy to maintain • Looks attractive • Incorporates the latest technology • Has many features	• Easy to produce • Uses available resources • Uses standard parts and methods • Uses existing facilities • Produces a minimum of scraps and rejected parts	• Meets consumers requirements • Easy to package, store, and transport • Is attractive • Suitable for display

Typical customer requirements include:

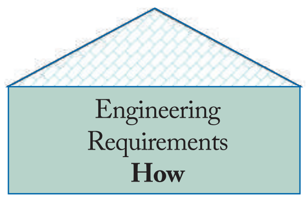
- functional performance (operational steps and sequence);
- physical requirements (available space, physical properties);
- life-cycle concerns (durability, maintainability, safety, failure rate, distribution, installation, repair);
- human factors (appearance, usage);
- manufacturing requirements (materials, quality, company capabilities); and
- resource concerns (time, cost, standards, equipment, environment).

Based on all the requirements obtained in this step of the design journey process, the final design/product must satisfy some of the requirements (MUST's) and accommodate some optional requirements (WANT's).

The customer requirements are generated through various information collection methods: observation, surveys, and focus groups as discussed in Section 4.3. In addition to the above collection methods, the design team may need to consult with professional organizations and experts in university and industrial settings, and review patents and research the design problem topic further by using library and Web resources.

3. Determine relative importance of the requirements—“Who vs. What” in the House of Quality. In this step, each of the requirements is evaluated with respect to their relative importance, and sometimes through weighted requirements when different customer groups are involved.

4. Identify and evaluate the competition—“Now vs. What” in the House of Quality. Here the goal is to determine how the customer perceives the competition's ability to meet each of the design requirements, called competition benchmarking. This step brings an awareness of what already exists related to the design problem.



5. Generate engineering specifications—“How” in the House of Quality. Engineering specifications are the measure of the customer's requirements. They are parameters that let the design team know if customer's requirements have been met. Without them, the design team cannot know if the product being developed will satisfy the customers.

6. Relate customers requirements to engineering specifications—“What vs. How” in the House of Quality. In this step, how the engineering parameters relate (strong, weak, or no relation) to a customer requirement is discussed.

House of Quality

What vs. How

Relationships
(Very Strong, Strong, Weak)

7. Set engineering targets—“How much” in the House of Quality. In this step, a target value for each engineering specification (or measure) is determined or set. These target values will be used to evaluate the product’s ability to satisfy customer’s requirements.

Engineering
Targets
How Much

Courtesy of Scott Adams—© Dilbert

Figure 4.7: Courtesy of Scott Adams – © Dilbert.

The following examples illustrate the QFD process and project planning.

Example 4.1 Consider a design of a multifunction peeler for use in a modern kitchen. Develop design specifications, and a project plan for the design.

Table 4.2 lists the customer requirements and the corresponding engineering specifications.

Table 4.2: Information for Example 4.1

Customer Requirements	Engineering Specifications
Lightweight	Weight is not more than 1 lb
Inexpensive	Cost is less than $5
Durable	Cutting blade can be used at least 10 years
Easy to operate	No moving parts
Ambidextrous	Sharp edge of the cutting blade can be adjusted for right- or left-handed people
Easy to clean	Dishwasher safe
Adjustable cut-depth	1–5 mm
Stained proof	Peeler is made from non-corroded material

Project planning

- Form a design team (material scientist, mechanical engineer, industrial engineer, manufacturing engineer, marketing person)
- Develop tasks (marketing survey, conceptual design, detailed drawing, evaluation).
- Research the market (patent, survey).
- Estimate schedule and cost (develop a schedule using Gantt chart, cost analysis).

Example 4.2 Consider designing a nature inspired robotic jumping mechanism, much as a robotic leg inspired by a grasshopper mechanism that would allow a small robot to jump over obstacles. Develop design specifications and a QFD chart for the design.

Following the steps in the design journey process, the QFD process was used to develop the customer requirements and the corresponding engineering specifications in Table 4.3.

The QFD chart is given Figure 4.8.

Example 4.3 The objective of this example is to "design" a three-seater transporter that can take UGA Engineering interns to various companies in the Athens area daily in the summer. Develop design specifications using QFD and complete the HOQ chart. You need to identify the customers and their requirements, benchmarks, and the engineering requirements and their targets.

Table 4.3: Information for Example 4.2

Customer Requirements	Engineering Specifications
Lightweight	Weight is not more than 8 g
Jump over small objects	Vertical jump height of 5 cm
Durable/reliable	Last for 5 years
Small scale	Leg height around 5 cm
Work in multiple environments	Resistance to temperature/humidity and extremes
Has net lateral movement	Minimum 1.5 m/s forward speed

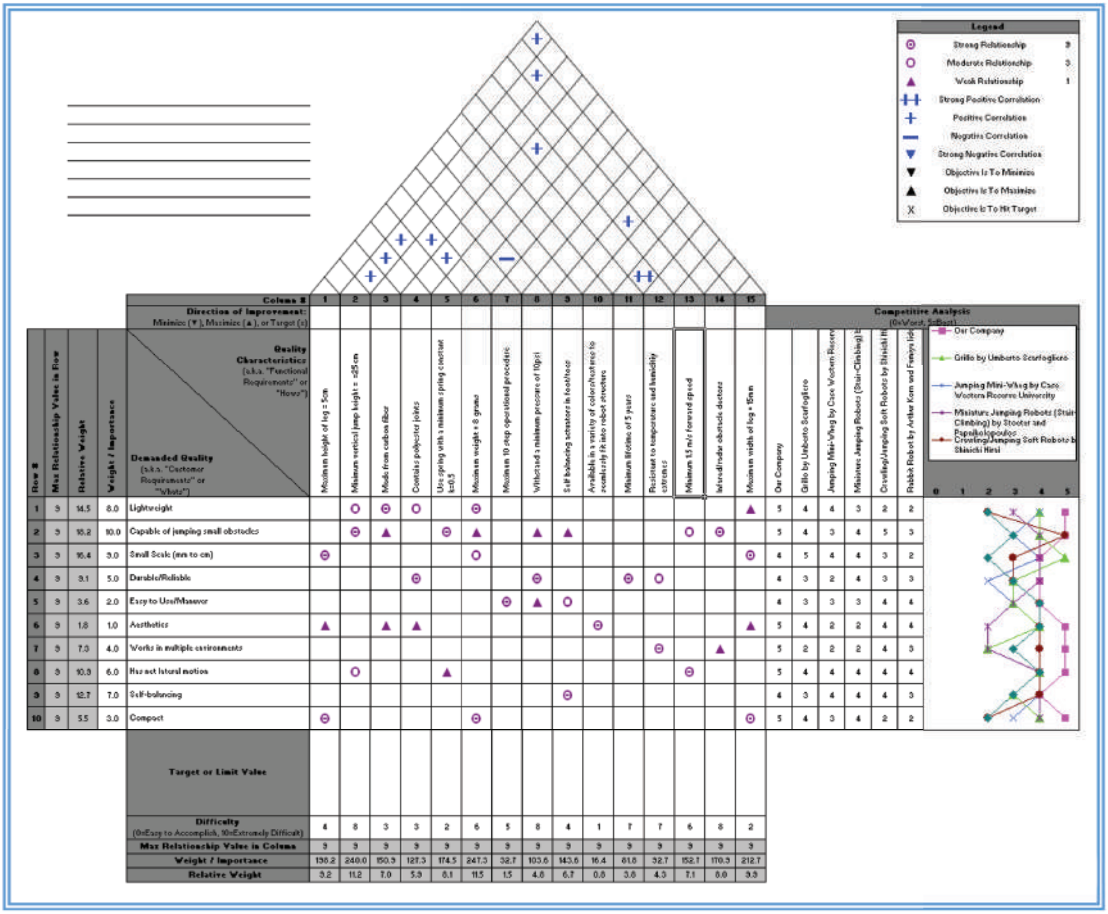


Figure 4.8: The QFD chart.

Solution:

Customers:

1. Student Interns
2. Transportation Department
3. Internship Companies in Athens area
4. Manufacturers
5. Athens Community/UGA

Table 4.4: Customer and engineering requirements along with targets following the QFD process

#	Customer Requirements	Engineering Requirements	Targets
1	Functional	Sustainable, HVAC	40–60 mph
2	Comfortable	Space to acommodate five people with enough leg/head room	10 ft^2
3	Safe	Safety features—airbags, seat belts, warning signs	At least two features
4	Inexpensive	Low cost	<\$2,000
5	Durable	Long lasting	7 years
6	Fast	Reasonable travel speed	At least 25 mph
7	Appearance/Aesthetic	Multiple colors and cool design, recycled materials	Modern, three colors
8	Easy to handle and maintain	Steering/transmission and minimum maintenance	Once a year

Benchmarks:

1. Ford Ecoline—Competitor #1
2. GA Buses—Competitor #2
3. Golf cart—Competitor #3

The QFD chart is given Fig. 4.9.

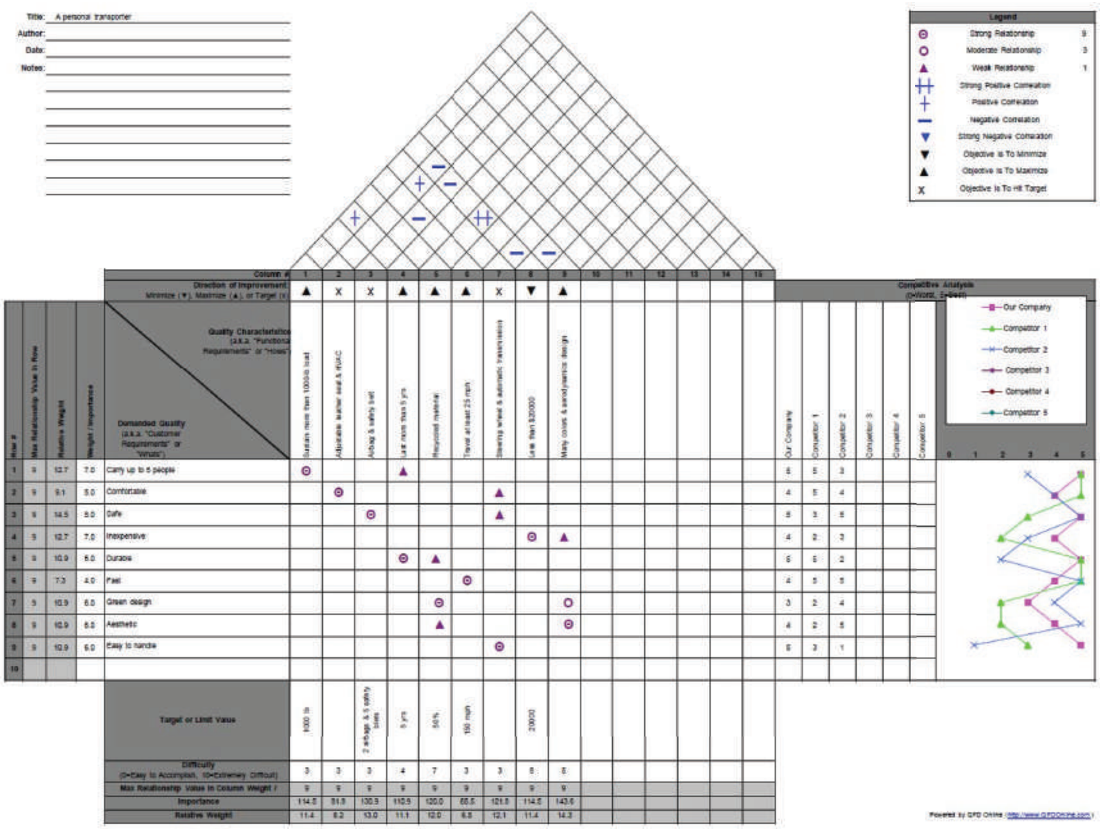


Figure 4.9: Table for QFD chart.

4.4 DESIGN REVIEW

Usually at the end of the design requirements step, a design project proposal is developed documenting the design need, customers/stakeholders and their requirements, and the engineering requirements that need to be met. A review of feedback/comments from all stakeholders is completed and once approved, the design team will move on to the next design step (conceptual design). The design review template at this step is given in Table 4.5. At this stage of the design journey, the outcome will be a project proposal and leading to the design as shown in Fig. 4.10. Typical templates for design project scope as well as design project proposal are presented in the next pages.

Table 4.5: Design requirements review template during the design journey process

Feature	Comments/Feedback
Establish Design Need: How are the needs identified and from what sources? Who are the stakeholders?	
Design Objective: What is the focus of the identified need? Write a design statement related to the scope of the project.	
Gathering Requirements: How was the information gathered? What resources were used to gather different requirements? Have constraints (time, budget, etc.) been identified?	
Project Planning: Does the design team have a project schedule and plans for next design steps?	
Target Users: Who are you designing for? Why are they important? What requirements need to be met? What are the engineering requirements and targets?	
Research the Market Questions: What key questions do you need to answer through your research? Who are your competitors/why is your design likely to be superior?	
Next Steps: Are there plans as to how the design concepts will be developed?	

Figure 4.10: Overview of the design need and requirements step of design journey leading to design project proposal and design review.

4.5 EXERCISES

4.1. What is the design journey process? Discuss/explain the steps.

4.2. Identify the steps in the design journey process for problems from everyday life (potato peeler, flashlight, ballpoint pen, bicycle, toaster, or toy). Follow the project scope opportunity template given in the next page.

4.3. Find four examples of designs from various engineering disciplines and describe the design journey process steps.

4.4. Develop the engineering specifications for designing a shelter for Hurricane Harvey victims in Texas.

4.5. Develop a House of Quality (HOQ) for the following products.

(a) A backpack for elementary school kids.

(b) A water bottle for traveling in third world countries.

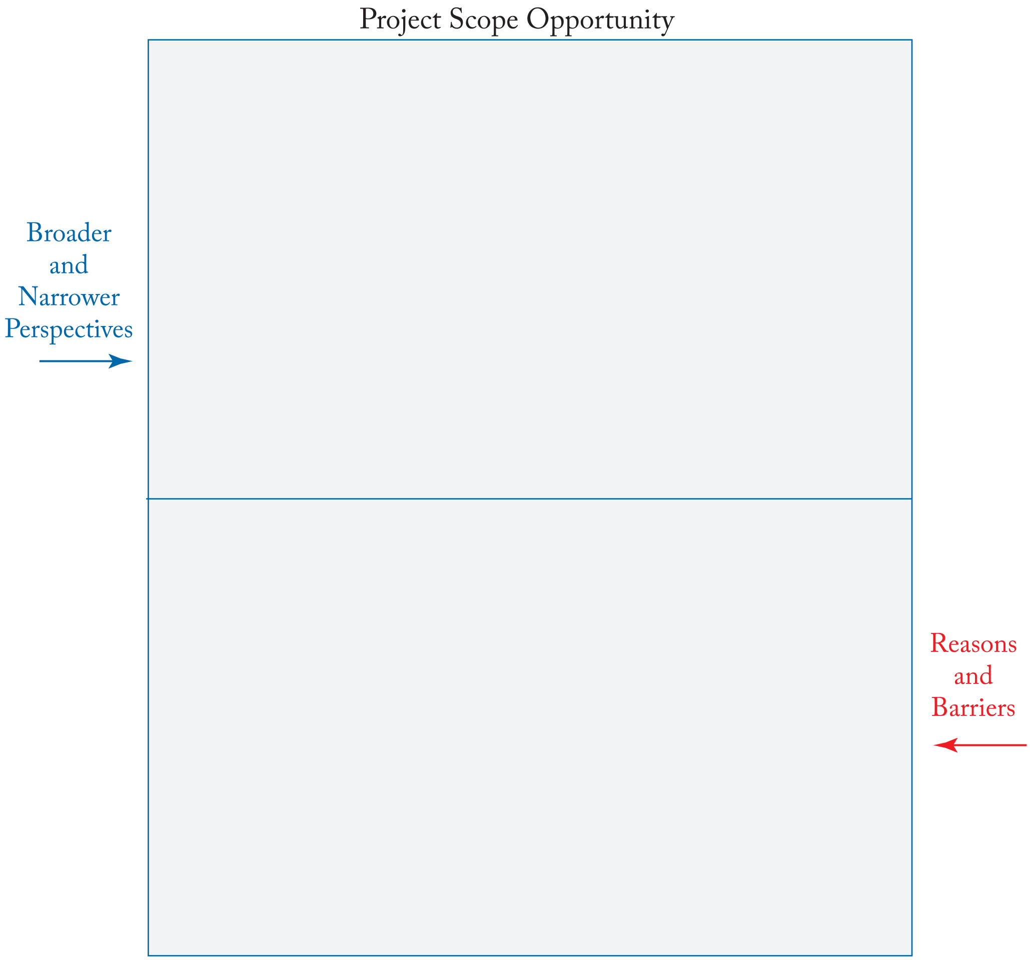
(c) A shelter for hurricane victims.

(d) A personal transporter to travel within a city.

Template for Design Project Scope

Start by thinking about your project theme in terms of opportunity, explore from broader and narrower perspectives, and reasons and barriers for the opportunity.

You might refine your scope after discussion with your team/stakeholders.



Template for Design Project Proposal

The design project proposal serves as a document for design specifications and for communication within the team as well as all stakeholders.

- ☐ **Project Description** — What is the opportunity? Project scope and objective?

- ☐ **Stakeholders** (Voice of Customers) — Who are the customers/what do they need/why is this important?

- ☐ **Exploration Questions** — Key questions through research; learn about stakeholders and their likes/dislikes, beliefs, etc.

- ☐ **Parameters/Constraints** — What parameters/constraints related functional, performance, cost, and environmental requirements are needed for the design?

- ☐ **Existing/Current Design Solutions** — Benchmarking/competitive designs/shortcomings?

- ☐ **Expected Outcomes (VALUE Creation)** — What outcomes should the design solution/innovation accomplish?

- ☐ **Project Plan and Schedule** — Gantt chart?

CHAPTER 5

Design Concepts

After reading this chapter, you will be able to:

- Generate alternate design concepts
- Evaluate various concepts
- List major techniques used in concept generation and evaluation

5.1 OVERVIEW

Potential and possible design solutions are identified during the conceptual design process and are discussed in this Chapter. The concept generation techniques are explained and illustrated with examples as needed, to facilitate real world implementation. Specific tools used for concepts generation and evaluation are discussed. The design review at the end of this step of the design journey is also presented.

5.2 DESIGN CONCEPTS – GENERATION

Based on a thorough understanding of the design problem using the QFD technique, several concepts (ideas) are generated from which a specific concept will be developed into a quality product. Figure 5.1 graphically illustrates the concept generation stage where many ideas/concepts are conceived using convergent and divergent thinking processes using various techniques in order to explore the complete design space.

Usually, the concepts come primarily from the designer's own knowledge and experience, but are usually enhanced through the use of the following methods.

- Brainstorming
- Using experts
- Patents
- Reference books and trade journals

It is important to mention that the design team should develop as many concepts as possible. In one of the student project, the design team generated as many as 15 concepts, out of which they eliminated 14 of them and the remaining final concept was further refined.

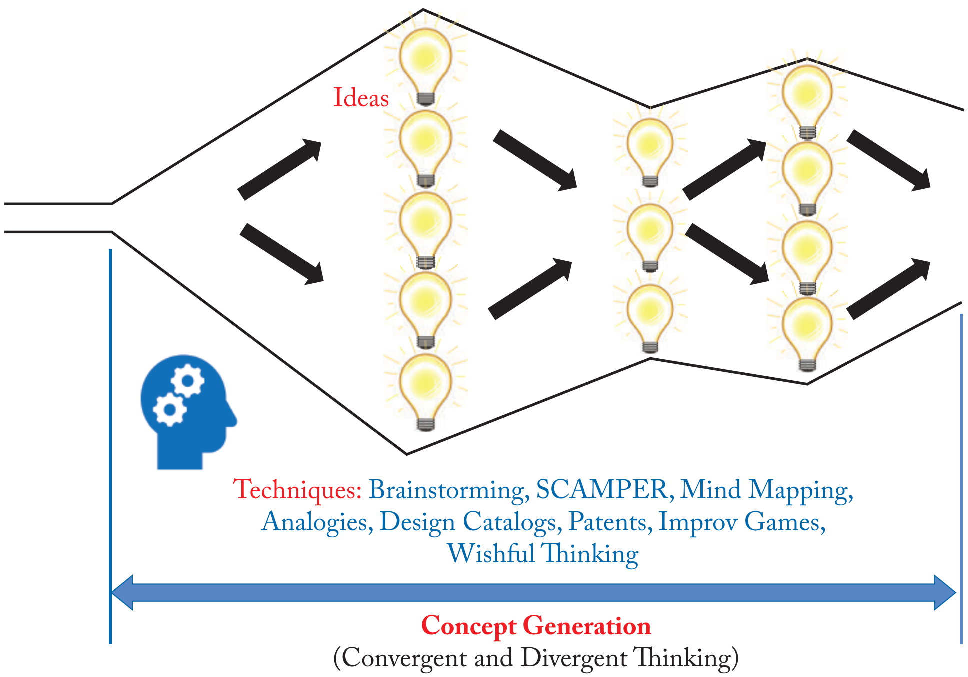


Figure 5.1: An overview of concept generation process.

Each of the developed concepts is evaluated based on the design specifications (customer requirements) discussed. Sometimes the concepts are refined during the evaluation process to generate more concepts. The procedure for concept generation and evaluation is iterative. The concept evaluation stage is the decision-making stage of the design process where the team as a whole, needs to select the best fit among the likely design choices for carrying out the design project.

Several methods may be used in selecting the final concept. One method may be to simply list the advantages and disadvantages of each of the concepts. A more sophisticated method involves the use of a decision matrix method where the desired performance criteria and their relative importance is listed. The decision matrix method is discussed in the next chapter under tools and techniques. Optimization methods may also be used in the decision making process. This phase of the design process concludes with identifying one or two concepts that are ready to be produced or developed into quality products.

CONCEPT GENERATION METHODS

The idea behind concept generation is to develop new ideas to solve the design problem/need. Concepts/ideas generated are subjected to further analysis during the concept generation phase of the design process. Available time and money for generating prototypes, computer models, or engineering drawings will need to be considered. Additionally, mathematical and engineering principles may be used to estimate the reliability of the data for the design project, and meet the form and function of the design. Some of the popular methods for concept generation are briefly described below.

BRAIN STORMING TECHNIQUE

Brainstorming technique is one of the common method used for generating concepts during the design journey process. In a brainstorming technique, all members of the design team should be fully encouraged to share any and all possible ideas (silly, crazy, and wild) they have for carrying out the design project. All ideas are equally considered and placed on Post-in notes or the white board (as shown in Fig. 5.2) for further discussion.

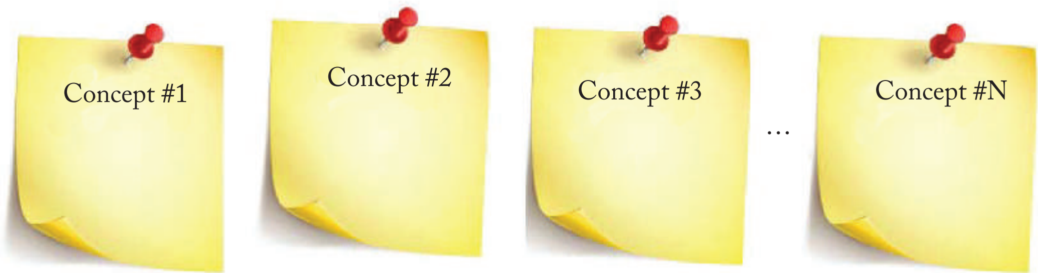


Figure 5.2: Concepts on Post-in notes for discussion during brainstorming session.

Usually, brainstorming session involves starting off with a set of trigger or structured questions that vary in nature from familiar to open/proactive issues related to the design challenge. Some typical questions include the following.

- How can we improve the idea?
- What is wrong with the idea?
- How can it be modified?
- Is it something we can adopt?
- How can we ensure every stakeholder is satisfied?

Example 5.1 Your design team is tasked with identifying possible uses for a grocery bag, as shown in Fig. 5.3. Brainstorm with your team to come up with ideas for multiple uses of a grocery bag.

Figure 5.3: A grocery bag example for brainstorming.

Solution:
After brainstorming with the design team, the following possible uses for the grocery bag were listed.

- Trash can
- Mask
- Wrapping paper
- Book cover
- To ripen fruit
- Storage containers
- Wallet
- Luminaries

SCAMPER *TECHNIQUE*

The SCAMPER brainstorming technique was introduced by Alex Osborn in 1996 in his book, *Applied Imagination*. This technique was later adapted by Bob Eberle and is now used often as a method for new idea generation. Each letter in the word SCAMPER serves as a prompt to the design team to ask a specific question, as illustrated below.

Substitute (what other materials, objects, or methods can be substituted)
Combine (what other combinations of uses may be possible)
Adapt (what other purposes may this product serve)
Minimize/**M**agnify (what features can be shortened, which ones made stronger)
Put to other uses (what other markets exist for this product)
Eliminate (what parts can be removed or eliminated)
Reverse/**R**earrange (what parts can be exchanged or reconfigured in a new pattern)

An example of using SCAMPER technique is presented below.

Example 5.2 A student's backpack pockets were ripped and there is a need to develop pockets for better organization with durable materials that are waterproof. How do you use SCAMPER technique to improve the design of the backpack?

Solution:

***S**ubstitute – New pockets with more durable pocket material*

***C**ombine – Combine more pockets into the straps and to add straps to the book bag*

***A**dapt – A protective space for the laptop*

***M**odify – Smaller pocket sizes for better organization*

***P**ut to other use – Travel bag or hunting pack*

***E**liminate – Pencil slots are too small—get rid of them*

***R**everse – Rearrange the zipping configuration*

MIND MAPPING TECHNIQUE

A mind map is a powerful graphical technique that provides a visual way to unlock the potential of our brain and can be used as a first step in representing the design problem. This technique was developed by Tony Buzan, a thinking guru who has written many books and is respected widely in many countries. Mind maps are more compact and help to make associations easily. They are also useful for consolidating information from multiple sources, thinking through complex problems, and presenting in a format that gives a big overall picture of the problem.

The mind mapping process involves the following steps.

- Start in the center of page and draw a central image that represents the design topic.
- Write the main themes around the central image similar to the chapter headings of a book.
- Start to add a second level of thought which is linked to the main branch that triggered them.

- Add third, fourth, … levels of data as thoughts come to you.
- Add emphasis to important points on the map.
- Outline whole branches of the map as you see fit.
- Make your maps a little more beautiful, artistic, colorful, or imaginative.
- Include humor and have some fun with the mind maps.

There are many books and software that are available for mind mapping applications. These include: Buzan's iMindMap; MindManager; MindMapper; MindView; XMind Pro; and others.

An example of mind mapping design problem is presented below.

Example 5.3 The hurricane/tropical storm Harvey in Houston/Florida caused lot of damage to houses and the local community, and made some people homeless. Imagine that you are working for a company that deals with disaster relief efforts. Consider the project of designing a smart shelter for a small size family who may live in the shelter for a week. Identify the basic problem-solving actions for designing and installing a smart shelter.

Solution:
Define the problem

- People are in a storm damaged location without access to food, water, and basic shelter.
- They cannot communicate with friends and family.
- They have lost everything and are in shock and disbelief.
- They might be injured.
- Everything is soaked.

Define the Conditions:

- Wet
- Foreign objects everywhere
- Electric lines down
- Septic tanks flood
- Underwater drainage floods
- Standing water

- Mud
- Humidity
- Hygiene
- Food storage and preparation

What are the primary necessities of life?

- Food
    1. Define Food
        (a) What foods will be needed for one week?
            i. How do we obtain/store food?
- Water
    1. Define Water
        (a) How much water will be needed for one week?
            i. How do we store water?
            ii. If water does runs out, how do we provide proper direction for finding water?
- Shelter
    1. Define Shelter
        (a) What type of shelter is needed?
            i. Protection from water and mosquitos
            ii. Protection from wind and further rain/flooding
- Identify secondary necessities of life
    1. Tools (to thermally regulate; heal wounds; navigate; communicate; stay in touch; cleanse; prepare/store food; rebuild, etc.)
- Identify site-specific issues pertaining to shelter
    1. Where will this go?
    2. Who will be using this?
    3. What size will this be?
    4. How many people need to be in one unit?

The mind map resulting from design team exercise is shown in Fig. 5.4 to further illustrate how mind mapping expands our thinking and understanding on the journey to find solutions.

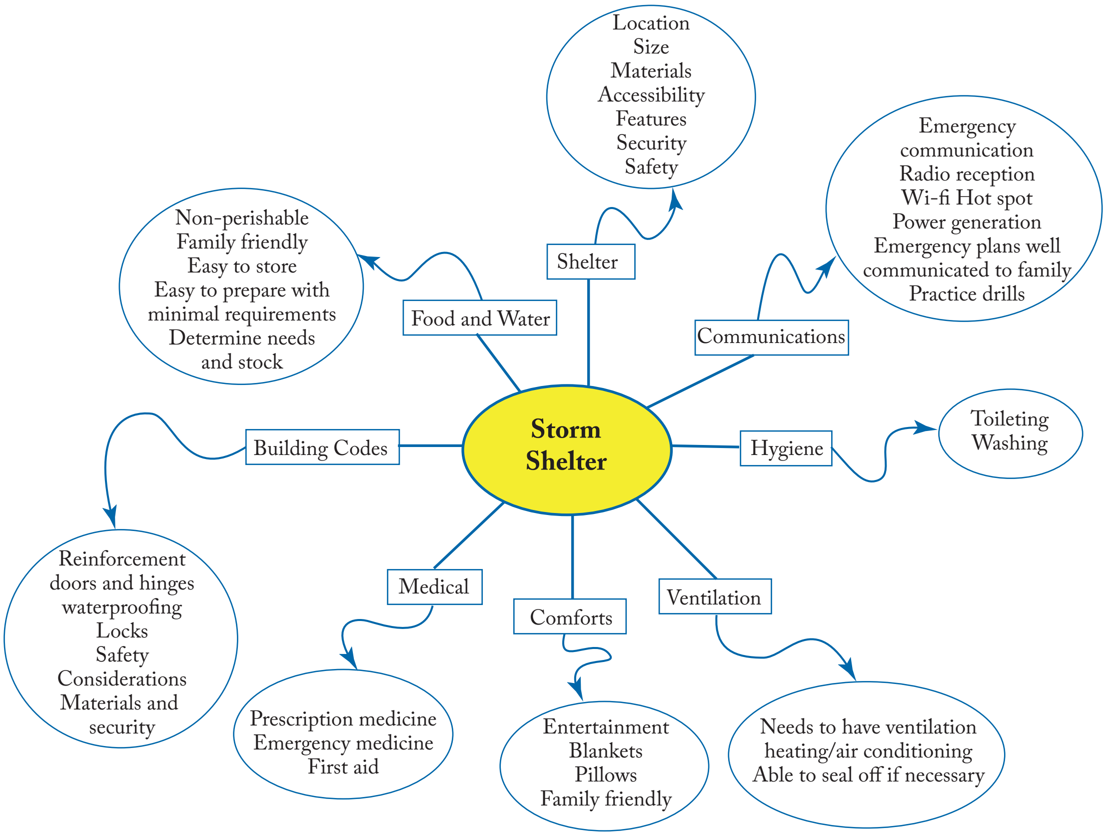


Figure 5.4: Mind mapping of storm shelter example.

PATENT SEARCHES

Another good source for generating concepts (ideas) is the patent literature. Reviewing patents usually takes time as there is a large body of literature on patents. All patents are organized according to their class and subclass numbers. It is interesting to note that all design patent numbers begin with the letter "D." The manual of U.S. Patent classification lists all the classes and subclasses. These also can be found in major public libraries and the following websites.

- U.S. Patent and Trademark Office: `http://www.uspto.gov`
- IBM Patent: `http://www.delphion.com/home`
- European and other foreign patents: `http://gb.espacenet.com/`

The following steps can be used as a guide to search patents based on a class or a subclass.

Step #1 -Identify the class or subclass of the area of interest.

Step #2 -Find the numbers of the specific patents that have been filed in the classes identified. This is done by using **C**lassification **A**nd **S**earch **S**upport **I**nformation **S**ystem (CASSIS), a computer index to the patent numbers. (Number, Title, and Abstract.)

Step #3 -For a specific patent number, either search the patent or the official GAZETTE. This is a weekly magazine that lists the abstract of each patent issued in an earlier week.

5.3 DESIGN CONCEPTS – EVALUATION

In order to identify a "good" concept that meets all the customer/stakeholders requirements, robust concept evaluation methods are required. The goal for the concept evaluation is to find a candidate concept that is customer focused, competitively designed, reduces time to production, and has buy-in from multiple stakeholders. Listing all the advantages and disadvantages of various concepts can be helpful in identifying the best candidate concept. Also, several computer-based optimization techniques are also available for evaluating concepts for complicated design problems. Figure 5.5 shows an overview of concept evaluation as well as the techniques used during this step of the design process.

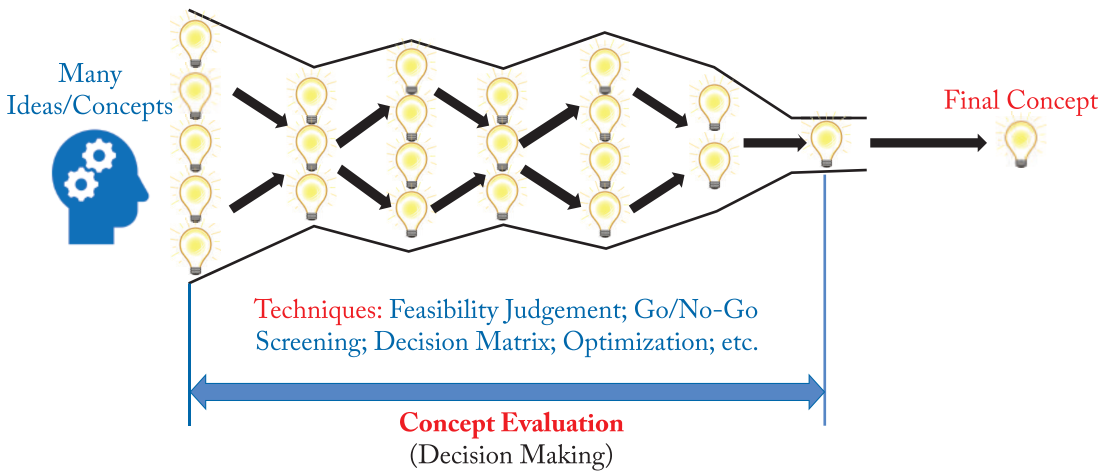


Figure 5.5: An overview of concept evaluation process.

Also, it is important to note that the feasibility judgement and Go/No-Go techniques provide an abstract comparison of concepts, whereas the decision matrix technique provides a relative comparison of concepts, as shown in Fig. 5.5. These techniques are briefly described below.

FEASIBILITY JUDGMENT TECHNIQUE

The feasibility technique is an abstract method for evaluating the concepts and is briefly described below.

- *It is not feasible, it will never work.*

  Before discarding consider BRIEFLY from different viewpoints. Ask:

  - Why is it not feasible?
  - Is it because the technology will not work or the concept does not meet the customer requirements?
  - Or is it that it is just "different" or not popular?

- *It might work if something else happens or changes*

- *It may be worth considering*

GO/NO-GO SCREENING TECHNIQUE

This technique asks if a concept can achieve and satisfy each of the customer (or engineering) requirements.
The answers should be:

- Go (yes or maybe) or no-go (NO).

- If a only a few no-go then consider modifying the concept to meet requirements.

DECISION MATRIX TECHNIQUE

The decision matrix technique is one of the methods used for evaluating the concepts generated during the design process. An overview of the decision matrix method or Pugh's method is presented in Table 5.1. This technique rapidly identifies the strongest concept, helps foster new concepts, and also helps improve understanding of customer requirements. The basic purpose of the decision matrix method is to provide a quantitative score for comparing each alternate concept relative to the other according to specified criteria (customer requirements). The steps in this method are summarized below.

Step #1: Choose the criteria (customer requirements) for comparison.

Step #2: Develop relative importance weightings.

Step #3**:** Select alternatives (concepts are represented as sketches so that they are at the same level of abstraction and in the same language) to be compared.

***Step #4*:** Evaluate alternatives using the following procedure.

Procedure:

- One of the concepts is selected as a datum or benchmark for comparison to others. The datum is selected based on the designer's choice (or favorite) or the existing design.
- Compare all other concepts with this datum by each one of the customer requirements.
- A score is given as follows.

    1. If the concept meets the criterion better than the datum, it is given a + or +1 score.
    2. If the concept meets the criterion as well as the datum (or there is some uncertainty), it is given an S (same) or 0 score.
    3. If the concept does not meet the criterion as well as the datum, it is given a − or −1 score.

Step #5: Compute satisfaction (the total score)

After a concept is compared with the datum for each criterion, four scores are generated.

- The number of plus scores.
- The number of minus scores.
- The overall total that is equal to the difference between the number of plus scores and the number of minus scores.
- The weighted total equal to the sum of each score multiplied by the importance weighting where "+" is treated as +1, "−" is treated as −1, and S is treated as 0.

The above scores can be interpreted in a number of ways.

- If a concept has a good overall total score, or a high "+" total score, it is important to identify what strengths it exhibits (i.e., notice which criteria it meets better than the datum).
- The grouping of "−" scores shows which requirements are difficult to meet.
- If most concepts get the same score on a certain criterion, examine that criterion closely. In fact:

    - it may be necessary to develop more knowledge in the area of the criterion to generate better concepts;
    - it may be that the criterion is ambiguous; and
    - it may be that different members of the design team interpret the criterion differently.

There might be a need to repeat the comparison with the highest scoring concept used as the new datum to further understand how the concepts compare to each other. This process of comparison is continued repetitively until the best concept or concepts are clearly identified.

It is important to note that the decision-matrix method is most effective if each member of the design team performs the evaluation independently and the individual results are then compared (adopted from Ullman, 2015 [24]). The results of the comparison lead to a repetition of the technique, with the iteration continuing until the team is satisfied with the results.

Table 5.1: Basic structure of a decision matrix technique for concept evaluation during the design process (redrawn from Ullman 2015 [24])

Step 1	Step 2					
Design Specifications	**Relative Importance**	**Alternatives**				Step 3
		Alternative 1	**Alternative 2**	**…**	**Alternative m**	
Criterion 1	xx	Evaluation 1-1	Evaluation 2-1	…	Evaluation m-1	Step 4
Criterion 2	yy	Evaluation 1-2	Evaluation 2-2	…	Evaluation m-2	
		…	…	…	…	
		…	…	…	…	
Criterion n		Evaluation 1-n	Evaluation 2-n	…	Evaluation m-n	
	Satisfaction	Score 1	Score 2	…	Score m	Step 5

Example 5.4 Hysterosalpingography (HS) is an outpatient procedure used to diagnose problems of both the uterus and fallopian tubes in women, which lead to infertility problems. Most often, the procedure is done to see if a woman's fallopian tubes are blocked or if the uterus has any abnormalities such as tumors, scar tissue, and tears. Using a HS Catheter, contrast media is injected into the uterus and fallopian tubes to highlight abnormalities such as size and shape. Thus, a HS Catheter should allow for injection of contrast media, a way to seal off the uterus from fluid leakage, and a mechanism to allow the physician to correctly form the shaft into shape.

Solution:

As part the design of the HS Catheter, the design team at IUPUI came up with the four design concepts, as shown in Fig. 5.6. The evaluation of the concepts using the decision matrix is shown in Fig. 5.7.

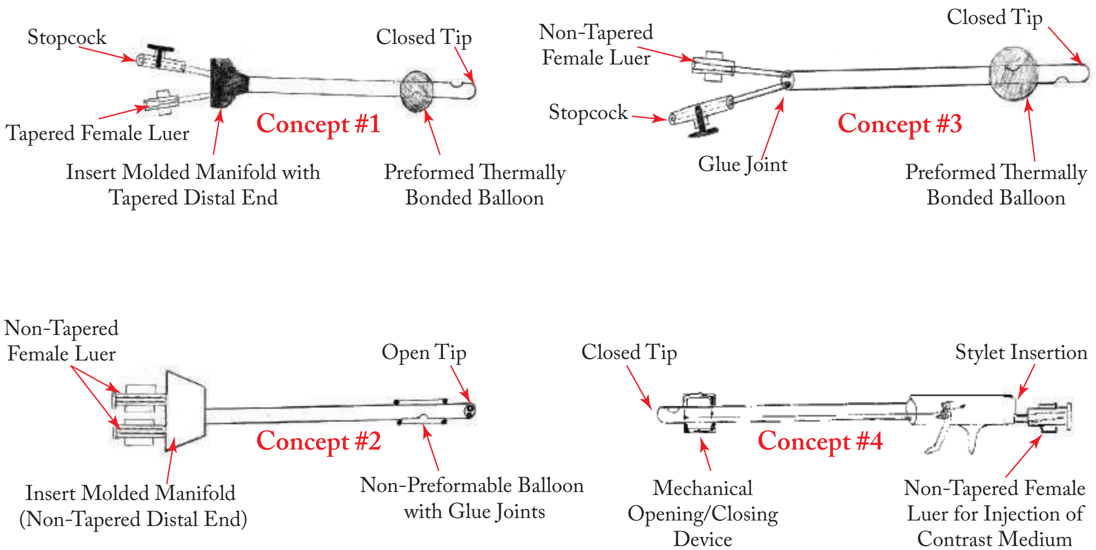


Figure 5.6: Design concepts for the HS Catheter (courtesy of IUPUI students).

Decision Matrix

Criteria	Importance	Concept #1	Concept #2	Concept #3	Concept #4
High quality/reliable performance/efficacy	9	+	0	Datum	0
Material compatibility w/ Contrast Media	7	0	0		0
Strong anchorage of balloon to catheter	7	0	-		-
Easy guidance & maneuverability of catheter	6	+	0		+
Easy guidance & maneuverability of outer sheath	6	+	0		0
Safe	9	0	-		0
Comfortable	7	0	-		0
Moderately priced	5	-	+		0
Reduce fluid leakage out of the uterus	5	0	0		-
Compatible w/ current sterilization techniques	9	+	0		0
Easy to manufacture	4	+	+		-
Meets FDA requirements	9	0	0		0
Method for injection of contrast medium	6	0	0		0
Size	6	0	0		0
Easy to package and transport	5	0	0		0
	Total +	5	2	N/A	1
	Total -	1	3	N/A	3
	Overall Total	4	-1	N/A	-2
	Weighted Total	+29	-14	N/A	-10

Figure 5.7: Evaluation of concepts for the HS Catheter using the decision matrix technique (courtesy of IUPUI students).

5.4 DESIGN REVIEW

Usually at the end of this concept design and evaluation process a design review takes place with all customers/stakeholders to review various design concepts and the rationale for the final candidate concept. The conceptual design review is presented in Table 5.2. Once everyone involved approves the final candidate concept, the design journey process will move on to the next design phase/step. This is presented in Fig. 5.8.

Table 5.2: Concept design review template during the design journey process

Feature	Comments/Feedback
Concept Generation: What techniques were used to generate concepts?	
Quality of Concepts: Were all concepts generated with quality to meet the requirements? Are there enough concepts generated spanning the design space?	
Evaluation of Concepts: How are the concepts evaluated? Did the team use customer requirements in their evaluation of concepts?	
Final Concept: Does the final concept meet all the requirements? Are there possibilities for concept refinement? Are there any plans to realize the final concept?	
Overall Innovation: How does the overall concept generation/evaluation process lead to innovation?	

Also, in the conceptual design phase, there is a need to represent the geometry of a product and evaluate its performance. For that purpose, geometric design tools such as AutoCAD or SolidWorks or ProE or Inventor software can be utilized to create, visualize, and manipulate the model through various modeling capabilities of the software.

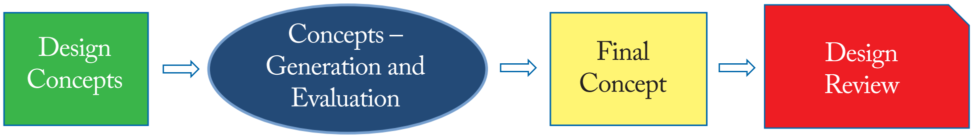


Figure 5.8: Overview of the design concepts generation and evaluation leading to final concept and design review.

5.5 EXERCISES

5.1. Consider a design project of a multifunction peeler for use in a modern kitchen. Develop design concepts using various techniques.

5.2. Develop the engineering specifications for designing a shelter for hurricane victims.

5.3. For Problem 5.1, evaluate concepts using the decision matrix method.

5.4. Develop at least ten concepts for a shelter to hold five people affected by hurricanes Harvey/Maria.

5.5. Evaluate the design concepts of Problem 5.4 using the techniques discussed in this chapter.

Design Activity Template – Conceptual Design

1. Write the design problem requirements.

2. Conceptual design. Brainstorm possible solutions.

3. Research the solution.
   (Patents, review of literature, analyze the solution for feasibility, safety, and implications)

4. Evaluate generated concepts.

5. Prepare final design concept and conceptual/CAD drawings or sketches.

CHAPTER 6

Detail Design

After reading this chapter, you will be able to:

- Understand the detail design process
- Be knowledgeable about designing for "X"
- Understand what design drawings are needed in the detail design
- Be knowledgeable about bill of materials
- Describe the CAE process for design analysis and evaluation

6.1 OVERVIEW

This chapter provides an introduction to the detail design process. Various computer tools available for design development and evaluation are introduced. Examples are also presented to better illustrate the principles involved in the detail design process. Specific design tools discussed in this chapter include detail design and evaluation, cost analysis, and CAE software tools.

6.2 DETAIL DESIGN

After design concepts have been generated and evaluated as discussed in the previous chapter, the candidate/final concept should be refined into an actual product or final design. The detail design and evaluation step emphasizes the importance of the concurrent design of the product and the manufacturing process, as shown in Fig. 6.1.

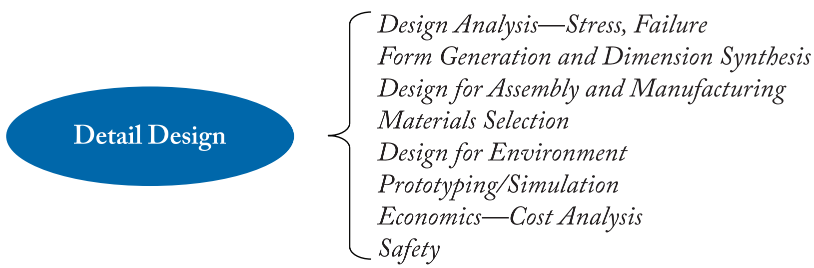


Figure 6.1: An overview of the detail design step of the design journey process.

In this step, detailed designs are developed for the candidate concept using dimension synthesis, mechanism analysis, design for assembly and manufacturing, material selection, stress and failure analysis, documentation, and evaluation. The knowledge base for developing a detailed product design comes from various courses in the engineering/design curriculum such as manufacturing, materials, economics, engineering sciences, and systems design. Design/product development is an iterative process. As products are generated they are evaluated for performance, cost, and production. Based on this evaluation, changes/refinements might be added as needed. Design evaluation may require that the design process return to developing engineering requirements or new concepts. Note that many design projects begin directly with product development without the benefit of prior specification or concept development. Such a design approach often leads to poor-quality products and in many cases causes costly changes late in the design process. Some of the detailed design aspects are presented below.

DESIGN FOR X: MANUFACTURING, SAFETY, FAILURE, AND ENVIRONMENT

When engineers design a product, they generally have to address several concerns such as cost, safety, reliability, assembly, tolerances, or the environment. The term "Design for X" is commonly used to refer to designing for these different concerns, with X representing specific attributes such as marketability, robustness, etc. Each of these attributes or factors is comprehensively addressed during different phases of the design process, and integrated under the "concurrent engineering" approach discussed in Chapter 1. Customized design procedures and methods available for addressing specific concerns such as manufacturing, safety, and environment are briefly discussed below.

DESIGN FOR MANUFACTURING

In *Design for Manufacturing (DFM)*, the focus is on minimizing production costs and time to market, while maintaining high quality. Several methods are used in DFM such as process-driven decision making and CAD/CAM technology to provide the design team with quantitative information (i.e., cost estimates for materials, pieces, tools) that will enable them to manufacture high quality products with minimum costs and in a shorter period of time.

DESIGNING FOR SAFETY

In *Designing for Safety*, the emphasis is on identifying and correcting potential process or product failures before they occur. Failure Modes and Effects Analysis (FMEA) is a stepwise procedure that systematically examines all the ways in which each part of a product may fail to perform as intended (a screw may come loose or become corroded, or a hydraulic hose may develop a leak for example). The procedure then provides an estimate of the adverse effects of these failures for the product and the user. For example, an open switch (failure mode) may cause a refrigerator to stop functioning, resulting in spoiled or wasted food (adverse effect). While some failures may result in minimal adverse effect, others may cause catastrophic damage. Effects analysis is therefore a very important tool that assists the designer in assessing and detecting the probability that the established controls or inspection procedures will catch the failures before they reach the customer. Calculations such as risk priority numbers are used to assess the part failure mode in a given product. Risk priority numbers are quantitative metrics that range between 1 and 10, with the smaller numbers denoting less risk of failure.

There are seven basic steps in the safety analysis process and are specified in a FMEA worksheet where all the analysis information and evaluation is recorded. For example, typical FMEA activities include the following:

- listing the system parts, boundaries, and requirements
- brainstorming potential failures
- using cause and effect diagrams to determine the effects of potential failures;
- identifying each component and its associated failure mode along with probability or failure rate for each failure mode
- reviewing and prioritizing failures to address based on factors such as safety, quality and cost
- developing a plan for taking corrective measures
- implementing and monitoring progress on the plan

Additional details regarding the FMEA method may be found in Eggert (2005).

DESIGN FOR ENVIRONMENT

Design for Environment is a recent outgrowth of greater societal awareness and legislative actions that place greater burdens on manufacturers to design eco-friendly and recyclable products. There is now greater attention paid at the beginning of the design process in estimating the costs associated with disposing or retiring products in a way that is not harmful to the environment once they reach the end of their shelf life.

DESIGN STANDARDS

When designing, students need to be aware of various standards that need to be followed in order for the design to be marketable and acceptable to customers. These standards many involve rules, policies, and guidelines and are recognized by professional organizations and state and federal governments agencies. A number of national and professional organizations require implementing standards in the designs that are applied to specific applications. Some of these include:

- American Society for Testing and Materials (ASTM)
- Institute of Electrical and Electronics Engineers (IEEE)
- American Society of Mechanical Engineering (ASME)
- American National Standards Institute (ANSI)
- National Transportation Safety Board (NTSB)
- US Food and Drug Administration (FDA)
- American Institute of Aeronautics and Astronautics (AIAA)

DESIGN EVALUATION – COST ANALYSIS

As part of the design process, it is important to generate a cost estimate and compare with the original cost requirements. Figure 6.2 shows the total cost (list price) for a product to reach the customer. All costs can be grouped into direct costs and indirect costs. Direct costs are those that can be specifically attributed to a specific component, assembly, or product. Indirect costs are not differentiated but are spread out over the entire life cycle of a product and include such things as overhead and marketing expenses. Examples of direct costs include costs for materials purchased, wages and benefits for hired workers and costs for tools.

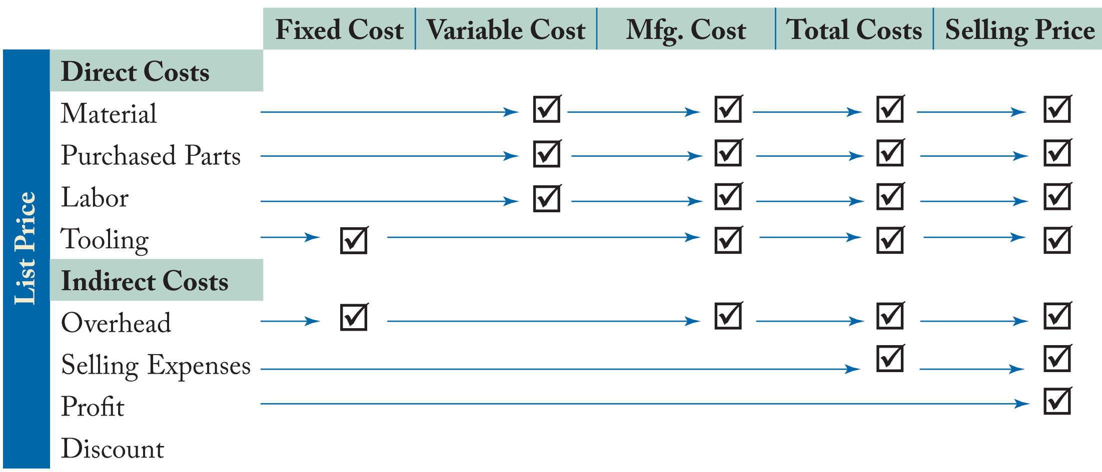


Figure 6.2: Overview of the product cost and its breakdown.

Another major category of costs commonly incurred are fixed vs. variable costs. Fixed costs do not change with the rate of production of products and typically include: investment costs (property taxes, insurance); overhead costs (general supplies, office personnel, rental charges);

management costs (costs payable to various staff from executive, legal, and research, and development departments); and selling costs (delivery and warehouse, technical service staff). Variable costs change with the rate of production and typically include costs for materials, labor, maintenance, power and utilities, quality control staff, patent or royalty payments, packaging and storage, and losses due to manufacturing defects. Cost estimation and analysis procedures are highly specific to individual organizations and agencies.

6.3 DESIGN DRAWINGS

As a necessary part of the design process, detailed design documentation in the form of drawings is the preferred method of communication among the design team members. Drawings also form the basis for analysis, manufacturing, and assembly of the final product. Additionally, the drawings may serve as means to simulate the operation of the product as well as checking for completeness and storing and retrieving the design. The following section discusses the typical drawings required by the design teams, which are usually drawn using CAD tools such as AutoCAD, SolidWorks, or Pro/E software.

LAYOUT DRAWING

This drawing defines the relationship of the developing assemblies and components. Layout drawings are the working documents that support the development of major components of the product design. The shape and size of the components, working space, and structural relationship will be shown in the drawings. A typical layout drawing is shown in Fig. 6.3. Layout drawings are drawn to scale using only important dimensions (spatial constraints). Tolerances are usually not shown on layout drawings. Notes are used to explain the features of the design.

DETAIL DRAWINGS

These drawings provide all the necessary information for part fabrication. As the product evolves (dimension synthesis) on the layout drawing, the details of individual components will emerge. A typical detail drawing (see Fig. 6.4) showing all the dimensions and tolerances drawn using standard ANSI Y14.5M, materials and manufacturing details is also presented in detailed drawings. A signature block is a standard part of a detail drawing to be approved by the management.

ASSEMBLY DRAWINGS

These drawings show relative locations of the parts and how the components fit together. Orthographic view is the most common type, as shown in Fig. 6.5.

Assembly drawing is similar to layout drawing but, with its own features. Each component is identified with a number or letter keyed to the bill of materials. Necessary detailed views are included to convey information that is not clear in the major views (cutaway drawing). Ref-

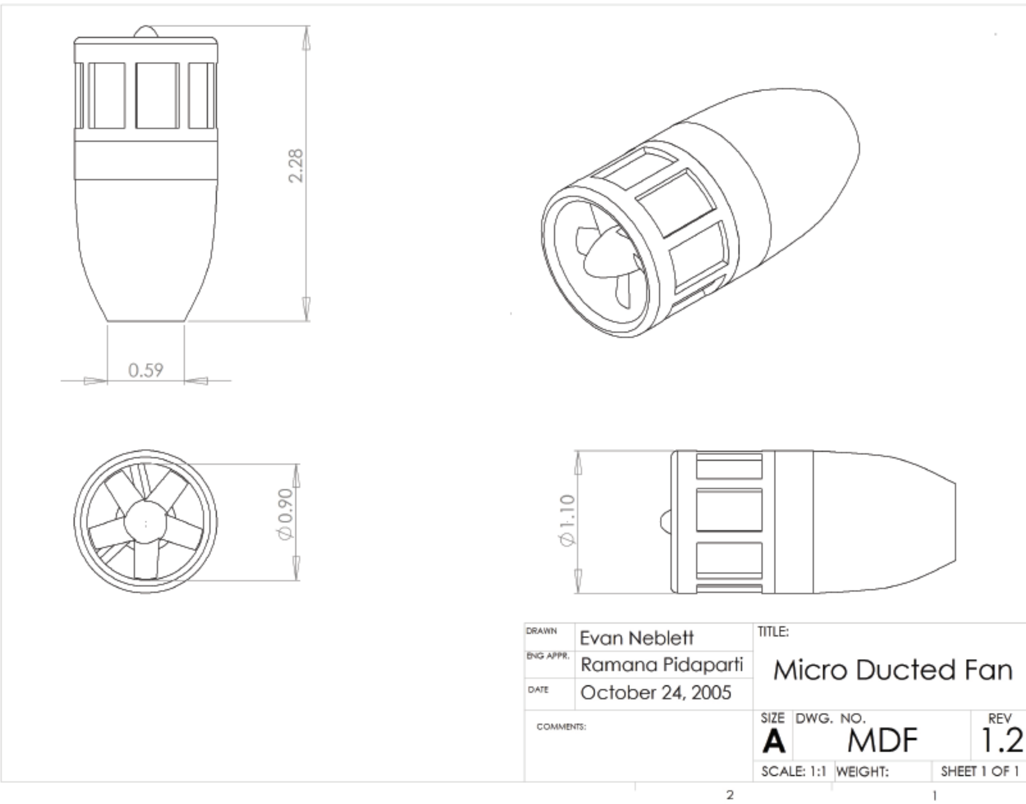


Figure 6.3: A sample layout drawing (courtesy of Evan Neblett).

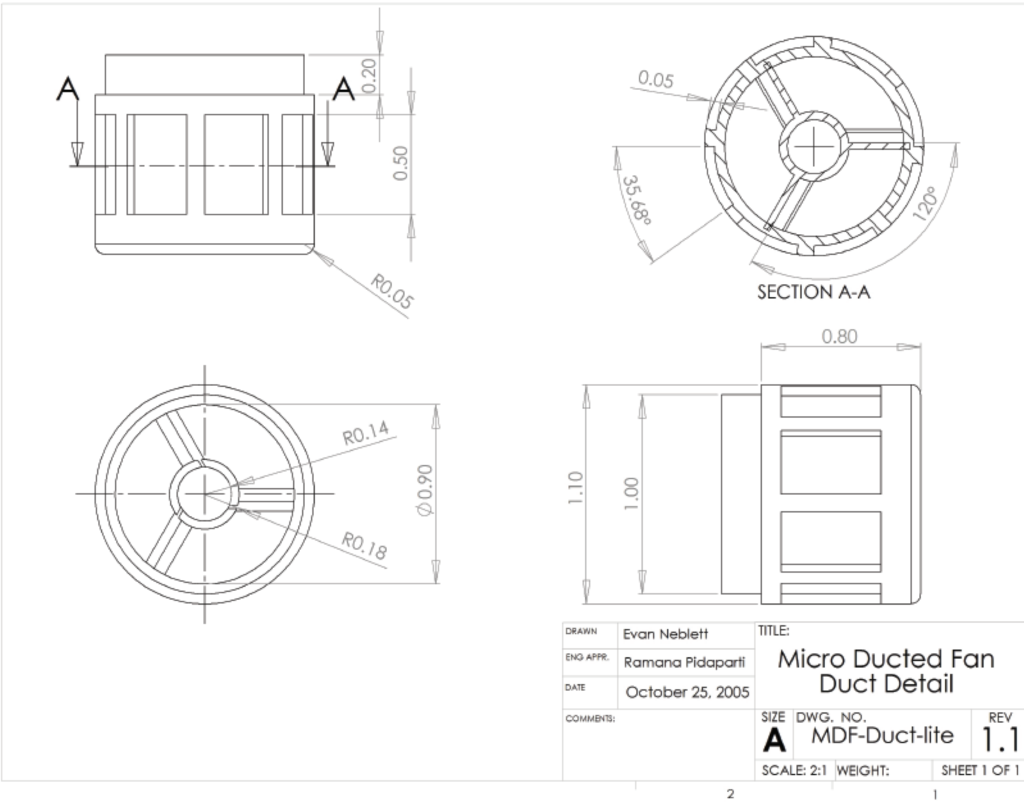


Figure 6.4: A sample detail drawing.

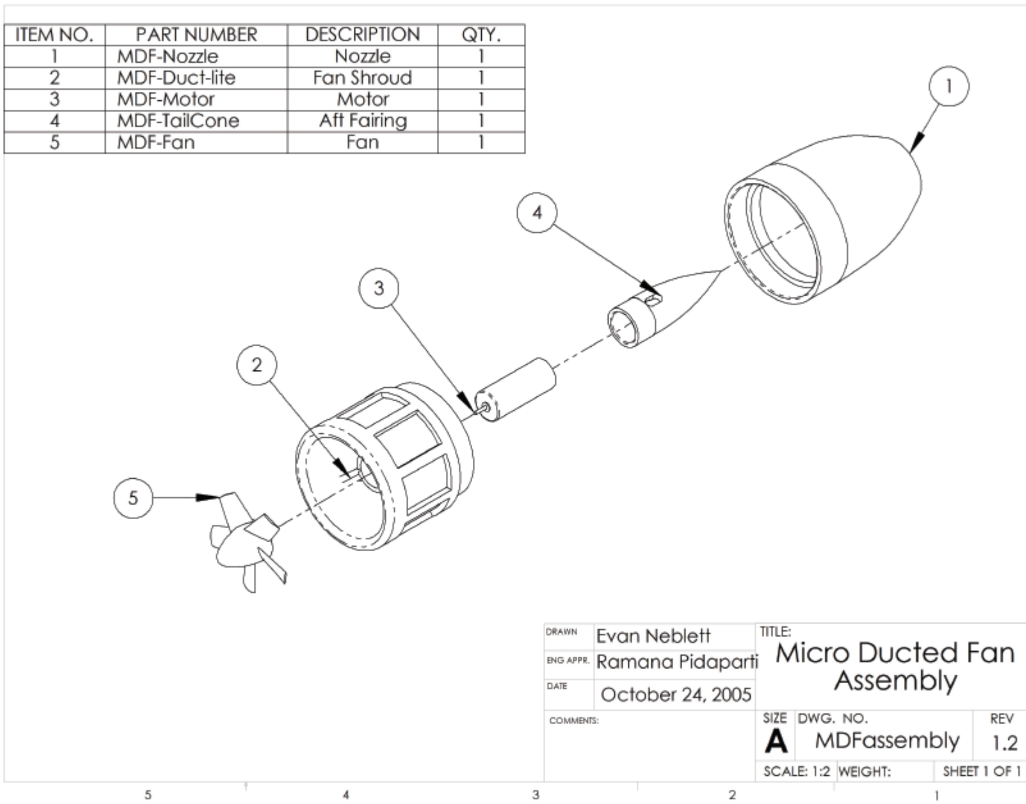


Figure 6.5: A sample assembly drawing.

erences can be made to other drawings and specific assembly instructions for additional needed information.

6.4 BILL OF MATERIALS

In the assembly drawing, the bill of materials (BOM) or parts list is included. The BOM is an index of the parts that were used in the product. The following six pieces of information should be included in a bill of materials, as shown in Table 6.1. A spreadsheet can be used to develop a bill of materials:

- The item number or letter (which is a key to the components in the assembly drawing)
- The part number (which is used throughout the purchasing, manufacturing, and assembly to identify the component)
- The quantity needed in the assembly
- The name or description of the components
- The material that will be used for the component
- The source of the component if it is purchased off the shelf

Table 6.1: Bill of materials

Item	Part	Quantity	Name	Material	Source
1	Body	2	Device Body	Metal	Hewitt Manufacturing, Inc.
2	LED	6	LED Bulb	Glass	Home Depot
...	...	...	...	...	...
...	...	...	...	...	...
12	Spiral Pin	10	Spiral Pins	Plastic	Lowe's

6.5 DESIGN ANALYSIS TOOLS

In the detail design and evaluation step, various analysis software and tools (ANSYS, ABAQUS, COSMOS, NASTRAN, MATLAB, or FEMLAB, and others) may be used to simulate the design analysis and evaluate stress and failure analysis for various material combinations. In addition, design optimization tools (DOT) coupled with design analysis tools are also available for the designer to generate optimum solutions. As part of the evaluation process, the designer can also generate bills of materials, specify tolerances, and perform cost analyses, while investigating the manufacturing tolerances of the design. Based on customer need for a specific product, the design team goes through the design process to come up with a design, which satisfies the customer requirements.

The manufacturing aspect of the product deals with fabrication, assembly, and testing. The manufacturing process also includes training, scheduling, and supervising production personnel with significant coordination among the design team, production planning, and manufacturing teams. Distribution activities include shipping the product to distribution centers located throughout the country and the world, from which the product is shipped to retailers or customers. Service activities are related to repair or replacement of products for customers. Disposal activities include removal or elimination or recycling the product.

COMPUTER-AIDED-ENGINEERING (CAE)

CAE software can help perform some of the steps in the design process, especially related to geometric modeling, analysis and synthesis. Table 6.2 shows the various CAE software tools used during the design journey process. CAE is a technology that uses computers to analyze CAD geometry, which allows the designer to simulate and study how the product will function and behave so that the design can be refined and optimized.

Table 6.2: CAE software tools during the design process

Design Phase	Goals	Tools
Conceptual Design	Geometric modeling, manipulation, visualization	SolidWorks, Pro/E, AutoCAD, etc.
Detailed Design	Animation, assemblies	SolidWorks, Pro/E, AutoCAD, etc.
Analysis	Structural, thermal, etc.	COSMOS, ANSYS, ABAQUS, etc.
Optimization	Structural	DOT, etc.
Evaluation	Dimensioning, tolerances, bill of materials, NC	CAD/CAM tools, rapid prototyping, simulations tools
Communication	Drafting, detailing, shading	CAD tools

Figure 6.6 shows an overview of the CAE approach to product design. CAE tools/systems are available for a wide range of analyses. These include dynamics analysis, finite element analysis, general purpose, and others. The dynamics analysis includes the kinematics of bodies that deals with motion and forces. Several dynamics analysis packages such as ADAMS, DADS, and Working Model can calculate the resultant motion of a design assembly having multiple moving parts by specifying the loads and using fundamental equations of dynamics and numerical methods. These packages can be used for analysis of positions, velocities, accelerations, contacts and collisions, joint forces, and relative motions. Then using CAD models, the motion can be displayed.

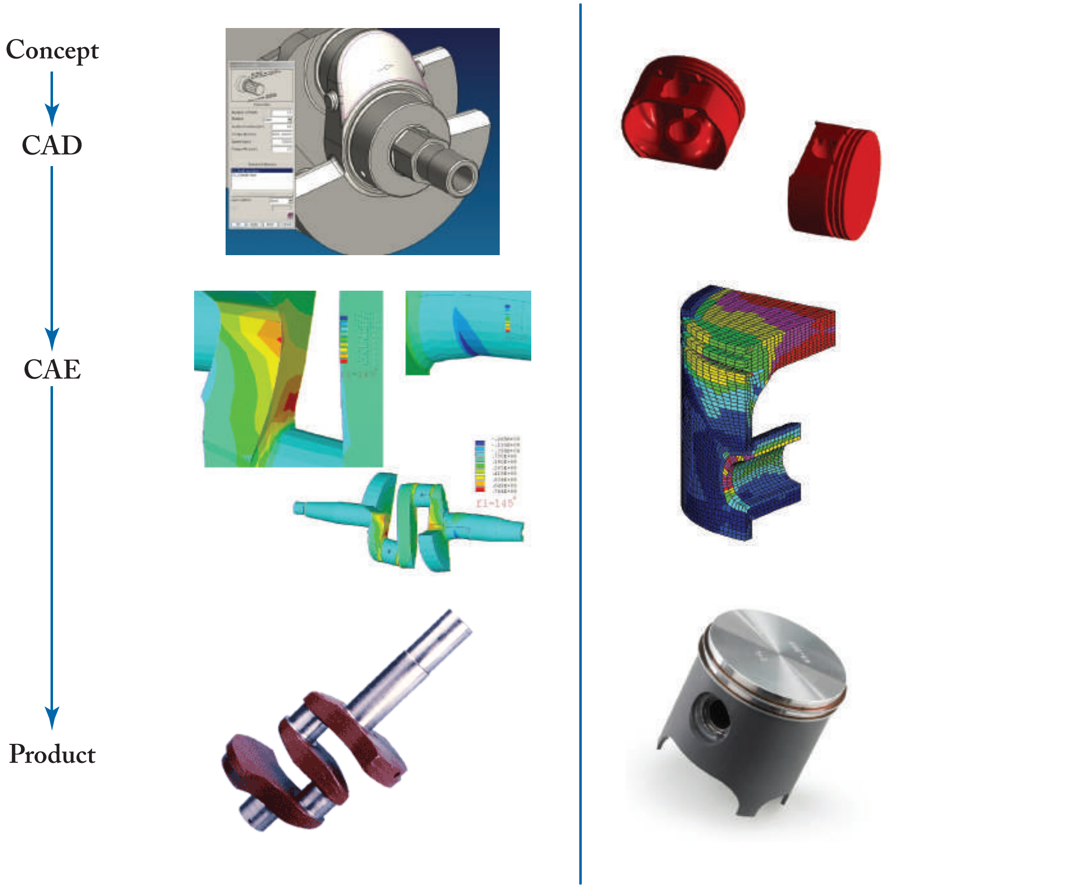


Figure 6.6: CAE approach to product design modeling and synthesis (source: `http://www.lozik.h1.ru/`).

Finite element analysis (FEA) is a method that predicts the behavior of a product subjected to loads. FEA is very popular and can find applications in the design analysis of mechanical, aerospace, biomedical, civil, and electrical systems. In general, in FEA, the shape of the designed part is broken down into smaller elements that are interconnected at nodes. In discretizing the part, the entire product shape is filled with elements without any overlaps, and analyzed for functional performance. To this end, the process begins with creating a geometric model of the part using CAD software (SolidWorks) and importing to analysis software (ANSYS) using `*.iges` file extension. The part is divided into a finite element mesh with smaller elements connected at nodes. After applying loads and boundary conditions to the part, the finite element equations are solved. Figure 6.7 shows the overall procedure for FEA and outlines the analysis results used to redesign the part. The FEA can be used for many types of analysis including

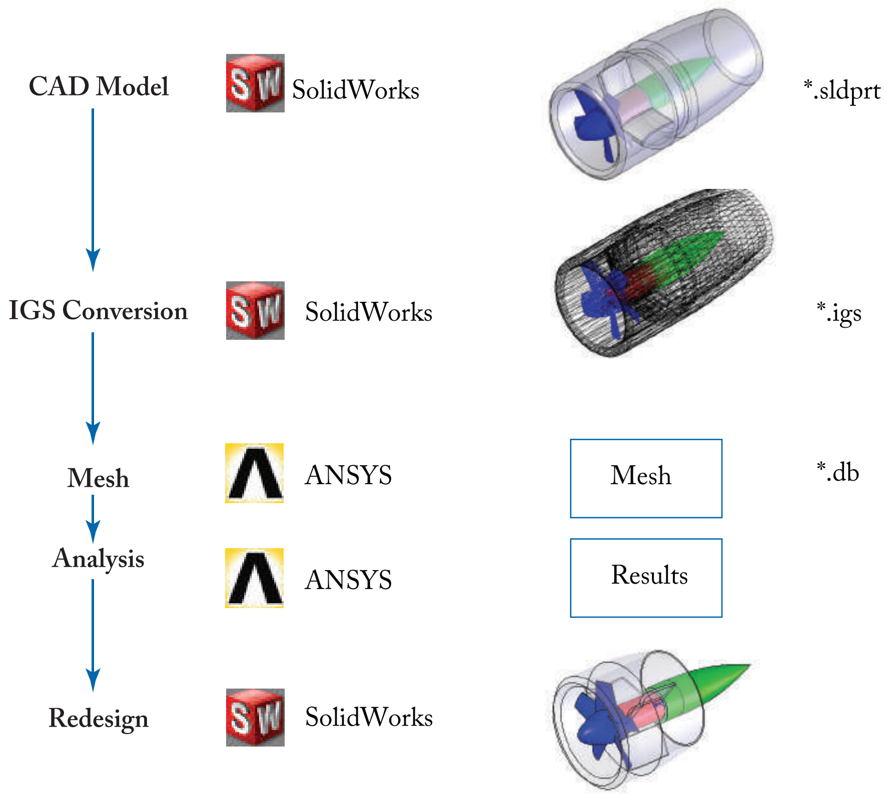


Figure 6.7: Overall procedure for redesigning a part using FEA.

stress, heat transfer, fluid flow, buckling, and vibrations. The factor of safety against failure can be predicted from the stress analysis. Figure 6.8 show examples of designs illustrating form, kinetic structure, and model for discretization of strength for CAE analysis.

General purpose software such as MSWord, MathCAD, MSProject, Excel, and PowerPoint are computer applications for word processing, mathematics, project management, spreadsheets, and oral presentations, respectively. Using the general purpose computer software, we can carry out the daily tasks very efficiently.

Other CAE applications, specific to a task, include GRANTA (for material selection), MATLAB Simulink (for systems simulation), DFMA (for applications involving design for assembly and design for manufacture), and QFDCapture (for quality function deployment).

In engineering practice, CAD/CAM/CAE has been utilized in different ways by different people to:

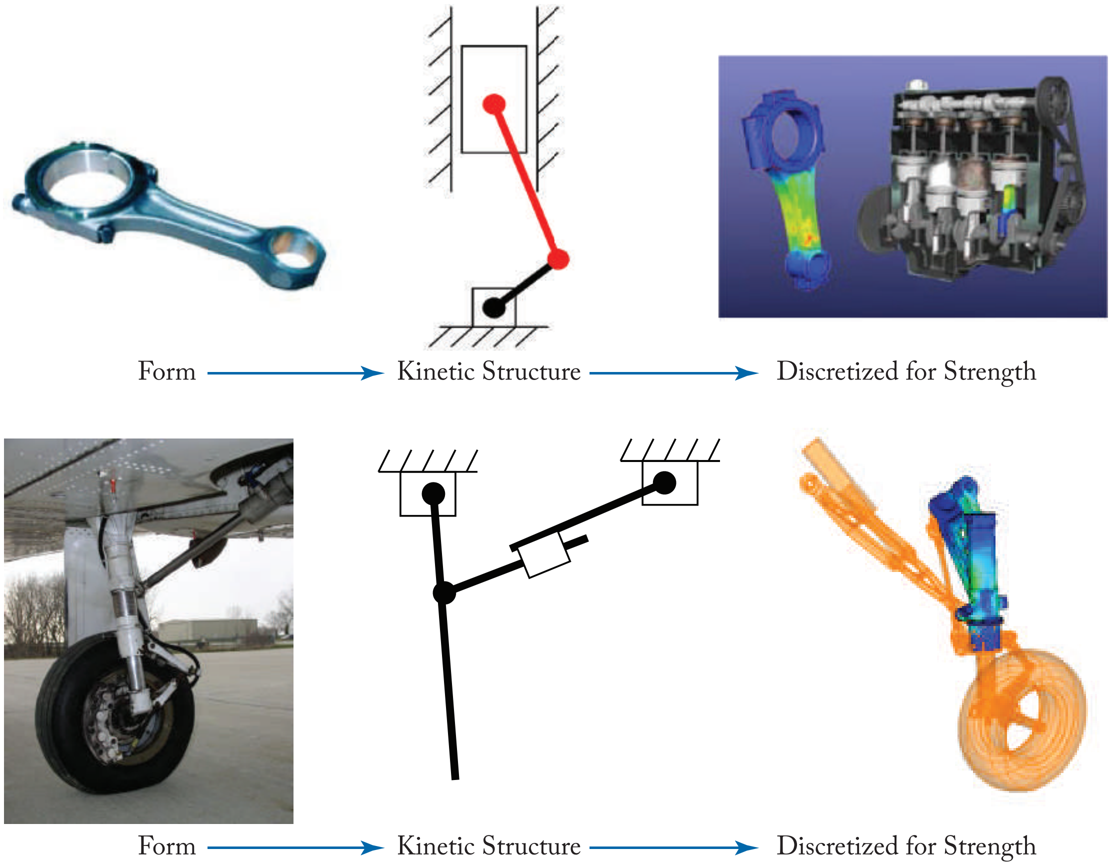


Figure 6.8: Examples illustrating the discretization of a part/form for CAE analysis.

- Produce drawings and document designs
- Generate shaded images and animated displays (i.e., as a visual tool)
- Perform engineering analysis (e.g., FEA)
- Perform process planning and generate NC part programs
- A combination of the above

6.6 FINAL DESIGN AND EVALUATION

Once the final design is selected and evaluated, the next step will be to make sure that all stakeholders (members of the design team, management, client, users, manufacturing, etc.) are provided sufficient details on the development and implementation aspects. The design process communication may be accomplished through oral presentations, face to face, or telephone conversations, progress reports, or formal project reports. Detailed documentation will need to be provided on the costs, material specifications, technical drawings of components or assembly, quality and reliability, and other design specifications as needed. Communication strategies and documentation details are described further in the next chapter.

IMPLEMENTING THE DESIGN DECISION

Before implementing a full-scale version of the final design, it may be helpful to develop and test a pilot model through rapid prototyping or working prototype or simulation to further identify technical specifications required to generate the best solution. Design projects being implemented in this day and age are increasingly requiring multidisciplinary interactions between engineers from various fields (e.g., business, electrical and computer engineering, chemical engineering, biomedical engineering). It is therefore important to keep in mind that communication skills are just as important to the success of a project as are technical skills.

VERIFYING AND EVALUATING THE DESIGN

The last step in the design process involves evaluating whether the design project met the required design specifications and performance criteria. A variety of methods including focus groups and satisfaction surveys may be used along with sampling or testing the product, process or system to ensure achievement of the optimum design. Typically, modifications and further refinement of the design will be required before the optimum design can be achieved. The closing step of the design process often marks the start of a new design process in search of the next generation of products, processes, and systems because technology changes so rapidly. New designs may be motivated with improved manufacturing processes and techniques, substitution of better materials with superior properties, or designs better able to satisfy the latest market requirements.

DESIGN STRATEGY

Due to the complexity in product design and conflicting requirements, the final product design needs to be selected based on tradeoffs among various requirements such as performance, cost, weight, robustness, manufacturing, implementation, aesthetics, etc. Different tradeoffs will lead to a variety of designs.

6.7 DESIGN REVIEW

Usually at the end of this step in the design journey process a design review takes place with all customers/stakeholders to review final design before releasing it to production, as shown in Fig. 6.9. The detail design review template is presented in Table 6.3.

Table 6.3: Template for detail design review step of the design journey process

Feature	Comments/Feedback
Detail Design: What aspects of detail design are investigated?	
What types of model/simulation and analysis techniques were used?	
What are the key features/function of the final design? How are they evaluated?	
How are the simulations/prototyping/testing being conducted to evaluate the engineering requirements?	
How will the design solution be realized?	
What steps in terms of manufacturing/materials will be adopted?	
Are there any design strategies followed for trade off among various criteria?	
How will the final design solution be implemented?	
Are there any risks/failure modes that affect the safety of the design?	
Design Innovation: How will the final design lead to innovation?	

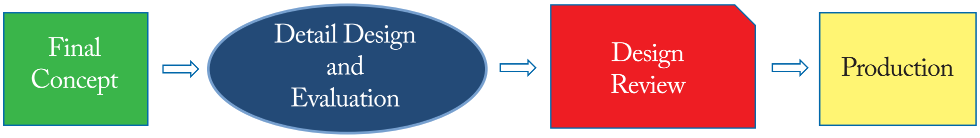


Figure 6.9: Design review after detail design and evaluation before the production.

6.8 EXERCISES

6.1. Explain the detail design process.

6.2. Conduct a cost analysis for a tiny house (200 square feet) for a family of two people.

6.3. What types of drawings are required as part of the detail design for a product?

6.4. Describe the process of creating a prototype from a CAD model.

6.5. List various types of prototypes for design evaluation.

CHAPTER 7

Design Communication

After reading this chapter, you will be able to:

- Understand the design reviews
- Understand the design documentation required
- Write a good design project report
- Make professional design project presentations

7.1 OVERVIEW

This chapter introduces the design reviews, tools, and techniques for documentation that are an integral part of the design journey process. Specifically, design reviews, documentation, and project report formats are presented. Based on the techniques discussed in this chapter, students should be able to effectively communicate and document the materials required during the design journey process.

7.2 DESIGN REVIEWS

At critical steps of the design journey process, design reviews are conducted with all stakeholders to ensure the design meets all the requirements related to the project. Usually, the design reviews are comprehensive and document processes intended to evaluate the design from multiple stakeholder's perspective and at the same time to identify any potential problems/risks. Detection of errors early in the design process may prevent unnecessary costs, failures, and the associate time spent on the projects. Usually, the regulatory agencies such as the American Society for Testing of Materials (ASTM) International and the Food and Drug Administration (FDA) conducts periodic design reviews that are very rigorous to make sure the design meets the requirements as well as appeal to consumers/users.

The number of design reviews depends on the complexity and scope of the design project. It is usually recommended that, at a minimum, design reviews should take place after at the end of design requirements, conceptual design, and detail design (as shown in Fig. 7.1) before releasing the design to production. Depending on the feedback received from various stakeholders, the design team may require to repeat previous design steps. Conducting the design reviews yields several benefits including the design team advancing to next step of the design process, providing meaningful feedback and guiding design improvements, and documenting the design processes checked for adequacy and validation.

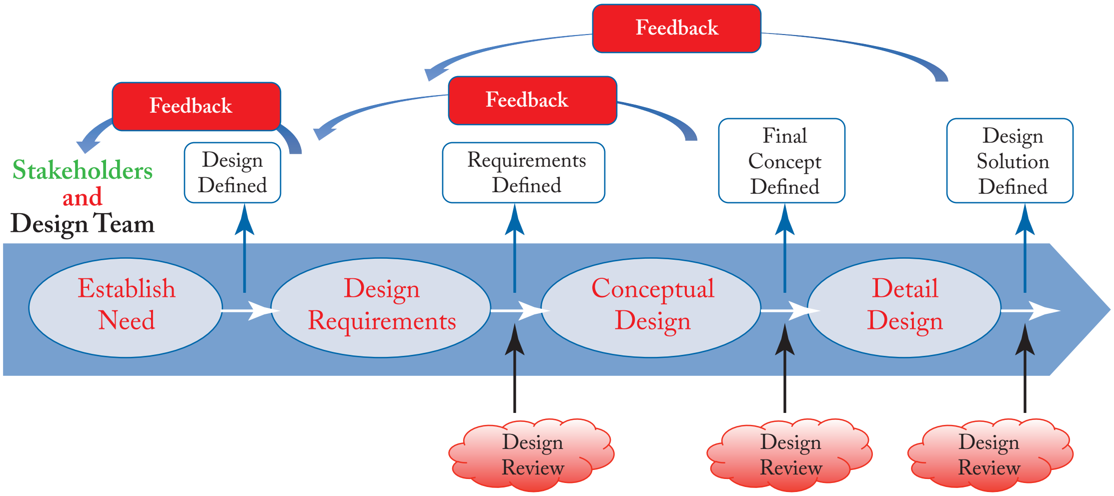


Figure 7.1: Design reviews at critical steps of the design journey process.

The design review templates for design requirements, conceptual design, and detail design steps of the design journey process presented earlier, in Sections 4.4, 5.4, and 6.7, can be used as a guide to seek feedback from all stakeholders as well as peers to further guide the design project.

7.3 DESIGN COMMUNICATION AND DOCUMENTATION

One of the key features of concurrent engineering is ongoing communication among the team members and communicating the right information to the right people at the right time. Figure 7.2 humorously illustrates the importance of communication during the design process. The following techniques may be used to foster communication among the team members during the design process.

1. *Design records*

   A design note book is usually kept to track the ideas developed and the design decisions made during the design process. The design notebook is a diary of the design. It should contain all the information including sketches, notes, and calculations that concern the design. Design records can be used for future reference to prove originality of patent application, and demonstration of the professional design procedures in case of law suits.

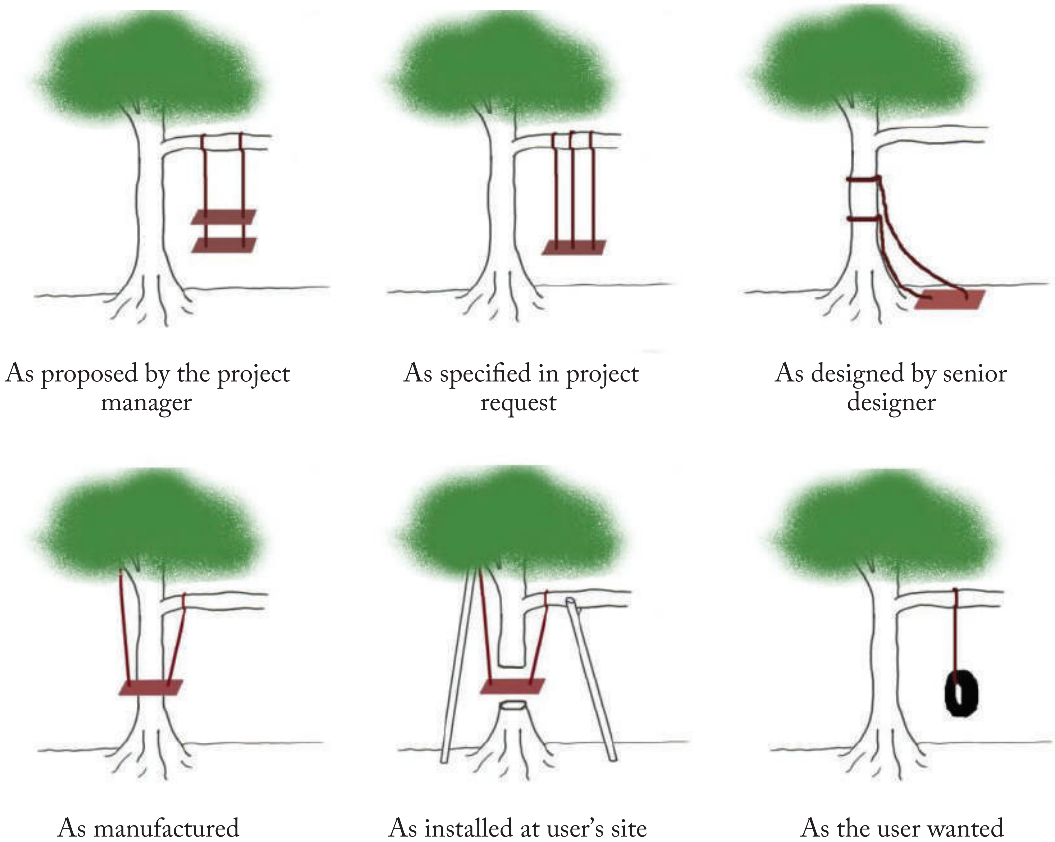


Figure 7.2: Importance of communication and documentation during the design process (redrawn from unknown source).

2. *Documents*

   During the design process, periodic presentations to managers, customers, and other team members will be made. These presentations are usually called design reviews, and usually include both written and audio/video materials.

3. *Documents communicating the final design*

   Final design documentation should include drawings (or computer files) of individual components (detail drawings) and of assemblies required to move the product to the manufacturing stage. Written documentation to guide manufacturing, assembly, inspection, installation and maintenance, and quality control aspects should also be maintained in this section.

7.4 DESIGN REPORT AND PRESENTATION

Communication skills, both written and oral, are very important in the engineering and scientific profession. The designers and the design team should be able to clearly communicate with all stakeholders as well as management or manufacturing teams, or clients or vendors following the development of a quality design. The following is a suggested format for student design reports.

PROJECT REPORT FORMAT

The outline of a typical project report is as follows.

Cover Page – Project Title, Names of Design Group, Address, and Date.

1. **Abstract (or Summary) –** Describe the goals or objectives of the design, the product developed, and its applications. Summarize the project's accomplishments.

2. **Introduction –** Summarize relevant background information including the need for the project. Clarify the technical design requirements and cost benefit analyses. State the project's objectives.

3. **Design –** Review the engineering specifications and targets; summarize and evaluate existing benchmarks with particular emphasis on any gaps which the project is intended to fill; discuss the concept generation and evaluation aspects of the project, followed by justification for developing the final product; provide a detailed description of the procedures used for product evaluation; and share the details of analysis, experiment, or field test results.

4. **Design for X –** Discuss how the product addresses a number of factors (X) such as cost, safety, sustainability, impact on the environment, and society.

5. **Conclusions –** Provide empirical evidence to support major project accomplishments and to demonstrate that the project has satisfied critical engineering specifications.

6. **Recommendations –** Discuss any recommendations you may have for extending/improving the design in the future.

7. **References –** Use appropriate professional style and language in citing sources (internet, books, journals, etc.) used in the design project. Provide an alphabetized bibliography of references at the end of the design report.

8. **Appendices –** Attach supplementary materials such as drawings (layout drawings, detail drawings, assembly drawings), design analysis results (stress contours, failure plots), product development plans, etc.

DESIGN REVIEW PRESENTATIONS

Keep these simple guidelines in mind when preparing design review presentations to managers, clients, and others involved in the design project.

1. Tailor your report to your audience—make it understandable to the recipient.
2. Carefully consider the order of presentation—present the whole concept, describe the main parts of the design, and tie all parts together into the whole design.
3. Be prepared with quality materials—use visual aids and written documentation, follow an agenda, and be ready for questions.

7.5 EXERCISES

7.1. What are the various design reviews during the design journey process?

7.2. Why do we have to conduct design reviews?

7.3. What kind of documentation is required during the design journey process?

7.4. What items should be considered for effective design project presentation?

7.5. Develop a design report for one of your projects from the previous chapter.

CHAPTER 8

Design Realization

After reading this chapter, you will be able to:

- Understand the design/product realization process
- Be knowledgeable about CAD/CAM
- Be knowledgeable about prototyping and testing
- Explain product data management
- Explain virtual engineering

8.1 OVERVIEW

This chapter provides an introduction to the design/product realization process. Various computer tools available for product development are introduced. The need for building and testing prototypes are discussed along with CAD/CAM tools for design process. CAD/CAM/CAE integration through a database using product data management as well as virtual engineering is also discussed.

8.2 DESIGN REALIZATION PROCESS

In previous chapters, we discussed how engineering design activities translate customer needs into a quality design following the design process. But, how is the quality design turned into a realized product? In today's modern design and manufacturing environment, most designed parts and components are mass produced. Design/product realization is a methodology by which both design and manufacturing processes are utilized to develop a product that meets customer needs. Figure 8.1 shows an overview of the product realization process. During the product realization process, original/redesigned or modified products are conceived, designed, manufactured, brought to market, and after they are in service for the designed life, they are disposed of or recycled.

To compete in today's market, products should be developed with quality, lower cost, and with shorter time to market. With the assistance of computer and information technologies, and rapid prototyping, industries make use of such capabilities as speed, memory, and graphics to automate product design and development. Computer-aided design (CAD), Computer-aided

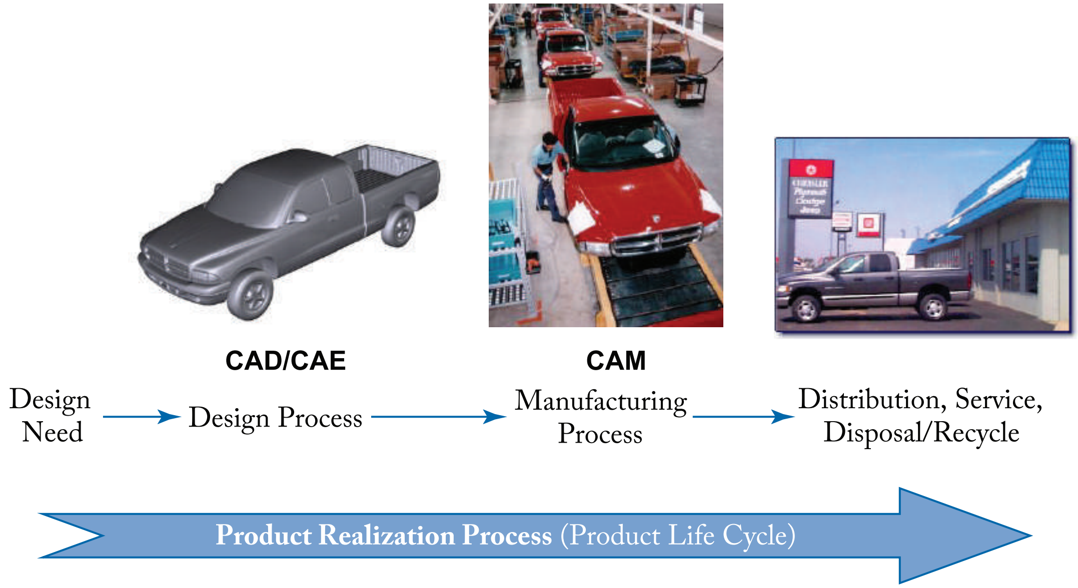


Figure 8.1: An overview of the product/design realization process.

manufacturing (CAM), and computer-aided engineering (CAE) are the technologies commonly used in the design/product realization process. Computer-aided engineering refers to computer software and hardware systems which are utilized to evaluate the functional performance of engineering designs. Sometimes computer-aided design (CAD) and computer-aided engineering (CAE) are easily interchanged. Prototyping and testing, product data management, business plan, and the virtual engineering are briefly described in the next sections.

8.3 COMPUTER-AIDED DESIGN (CAD) AND COMPUTER-AIDED MANUFACTURING (CAM)

Computer aided design (CAD) and computer-aided manufacturing (CAM) processes and tools are commonly used in many engineering tasks including the design and development of a product based on consumer needs and market demands. CAD processes are typically defined as a subset of the product design process, while CAM is a subset of the product manufacturing process. Geometric modeling, computer graphics, and design form the three core disciplines contributing to CAD systems, while manufacturing, automation, and CAD contribute largely to CAM systems. The various tasks in CAD and CAM are shown in Fig. 8.2.

CAD systems consist of both hardware (computer and mouse) and software (computer programs usually written in C or C++) components, and add to the complexity of CAD/CAM system applications. CAD/CAM systems can be used to create the geometry of a product, run analyses, or perform selected computations. CAD/CAM software typically has a GUI (graphical user interface) that enables users to interact easily with menus and icons to perform engineering design tasks across all platforms and operating systems including UNIX, Linux, Windows, and Apple. You can purchase software that is compatible with your particular operating system.

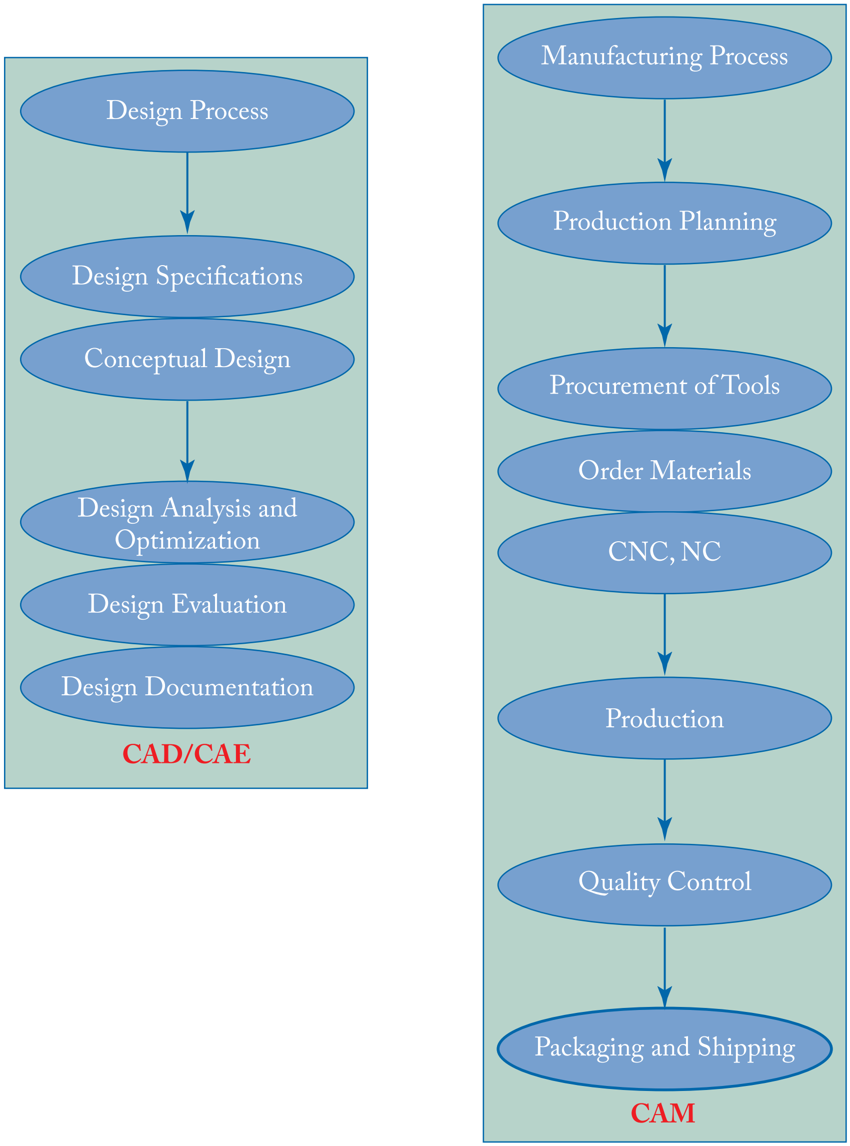


Figure 8.2: Various tasks involved in CAD/CAE and CAM processes.

CAD is the technology that uses computer systems to create, modify, analyze, and do the optimization to redesign the product. Various geometric modeling schemes can be used to develop a design and prepare 2D and 3D drawings of product parts and assemblies. CAM is the technology that uses computer systems to plan, manage, and control manufacturing operations and connects them with production plant resources. One of the primary functions of CAM is to generate the operations required to control a machine for milling, grinding, cutting, bending, or turning a raw stock into a finished product through an NC or CNC machine. The CAM software can generate the instructions for the machine through a CAD database plus the machine code. Usually, CAM operations are based on 2D geometry extracted from the 3D solid model. The extracted 2D geometry is stored in a `*.dxf` file that can be read by the CAM software. The CAM software will generate the CNC code for the CNC mill/lathe. Once a CNC code is generated, then the tool path will be created from which the part/design is produced through the CNC machine.

CAD/CAM TOOLS

Table 8.1 shows the CAD tools (geometric modeling and graphics) and the CAM tools (geometric and CAD, NC programs, robotics) required to support the design and manufacturing processes during product realization.

Table 8.1: CAD/CAM tools required to support product realization process

Design Phase	**Required CAD Tool(s)**
Conceptual design	Geometric modeling techniques, graphics aids, manipulations, and visualization
Design modeling and simulation	Same as above, animation, assemblies, special modeling packages
Design analysis	Analysis packages, customized programs, and packages
Design optimization	Customized application, structural optimization
Design evaluation	Dimensioning, tolerances, bill of materials, NC
Design communication and documentation	Drafting and detailing, shaded images
Manufacturing Phase	**Required CAM Tool(s)**
Process planning	Computer Aided Process Planning (CAPP) techniques, cost analysis, material, and tooling specification
Part programming	NC programming
Inspection	Inspection software
Assembly	Robotics simulation and programming

8.4 PROTOTYPING AND TESTING

Prototypes are generally classified according to the degree to which they are physical replicas or models of the product vs. analytical or mathematical models and how many attributes or dimensions of the product they represent (full-scale or comprehensive models vs. focused prototypes that examine only selected attributes). Companies therefore spend a lot of time and money in defining what prototypes to build and test in response to specific questions about form, fit, and function of their products.

Engineers *prototype* a design, industrial designers *prototype* their concepts, and software developers write *prototype* programs. The rapid prototyping process produces scaled physical prototypes of CAD designed parts. Rapid prototyping reduces the time and expense involved with the tooling to make designed parts.

Building and testing prototypes of concepts, designs, and programs is an integral part of new product development. Prototypes are the closest or best approximations of the actual product to be launched on the market, and are useful tools for testing the product's form (appearance, style), fit (parts of the product mesh easily in a user friendly manner), and function (meet performance requirements as specified with minimum wear and tear). Using prototypes to answer these questions early in the product development cycle is vital to the economic and technical success of the new product.

Prototypes can be used for learning (will it work or meet the customer needs?), to assist the product development team in gaining new knowledge regarding issues related to the product's manufacturability and performance, improve communication at all levels of the design team (management, vendors, engineers, customers, etc.), and serve as milestones for demonstrating the level of functionality of a given product.

The overall rapid prototyping (RP) process is shown in Fig. 8.3. It begins with the creation of a virtual part using 3D solid modeling computer techniques. The part shape is stored as a data file with `*.STL` file extension in the computer. All the surfaces of the part are converted to very small triangular facets. The converted `*.STL` file is read by a computer program specific to a rapid prototyping machine, such as 3D Systems or CNC machine. The RP machine processes the `*.STL` file by creating sliced layers of the model. The physical model is created by processing one layer at a time.

RAPID PROTOTYPING – ADVANTAGES AND DISADVANTAGES

The advantages of RP include time savings (compared to a physical prototype), duplication ease and low costs (duplicate prototypes can be fabricated quickly with less expense), flexibility (to changes during next iteration in designs) and rapid tooling (for production and facilities planning and communication for tooling due to data stored in electronic form). The disadvantages of RP are the initial costs of purchasing and setting it up, and the cost of the prototyping materials.

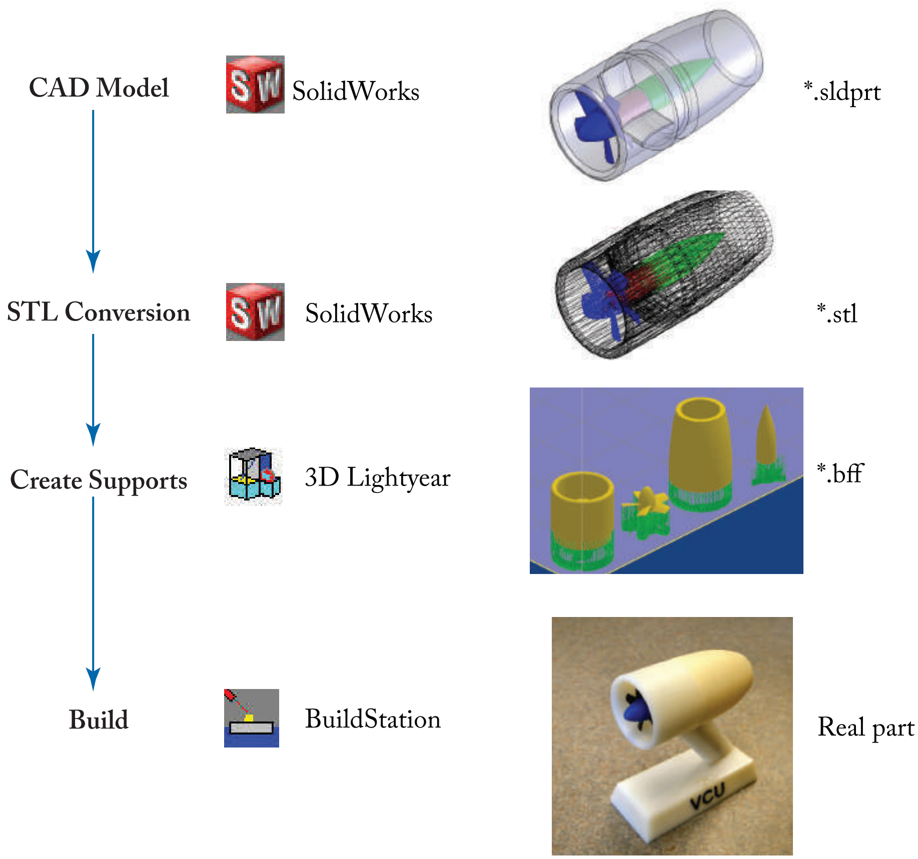


Figure 8.3: Prototype building starting from a CAD model.

TESTING PROTOTYPES

A design-build-test strategy is commonly used in new product development and particularly with prototypes that can answer questions about the product's form, fit, and function. Prototypes are subjected to specific tests to answer questions about mechanical modes of failure, manufacturability, operation/maintenance, safety and environmental impact. A test plan document is also developed that details the types of tests to be performed along with the timelines for completion, and the resources required. This document should include at a minimum, information related to the objectives of the testing program, the scope of the work to be completed, the budget, and a timeline schedule. A template for design evaluation of prototype testing is presented in Table 8.2.

Table 8.2: Feedback from prototyping on the design evaluation

User:	
What worked?	
What didn't work?	
Which of your needs did the prototype meet?	
Is the prototype useful?	
What would you change, if anything?	
Other feedback?	

8.5 PRODUCT DATA MANAGEMENT

Computer systems designed to manage both product and process information related to a specific product are referred to as Product Data Management (PDM) systems. PDM's are database programs that manage documents and files (PDF, CAD files, FEA files, and CAM files), store product structure, design history, and processes in a database environment (see Fig. 8.4). PDM's support the activities of product teams with techniques such as concurrent engineering, and can be used by cross-functional teams to manage product-related data and development processes. PDM is organized by product and it manages specifications, part information, Numerical Control (NC) programs, CAD, models, spreadsheets, test results, electronic images, and paper documents throughout the life cycle of the product. In general, PDM may help to reduce the time and cost of new products as well as improve the quality of products and services.

8.6 BUSINESS PLAN

The first step on the path to the successful product or business requires creating a business plan. A business plan is also necessary for entrepreneurs who are just starting out or need funding or to monitor the product development business. The various elements of the business plan are briefly described below.

1. Executive Summary
2. The Company

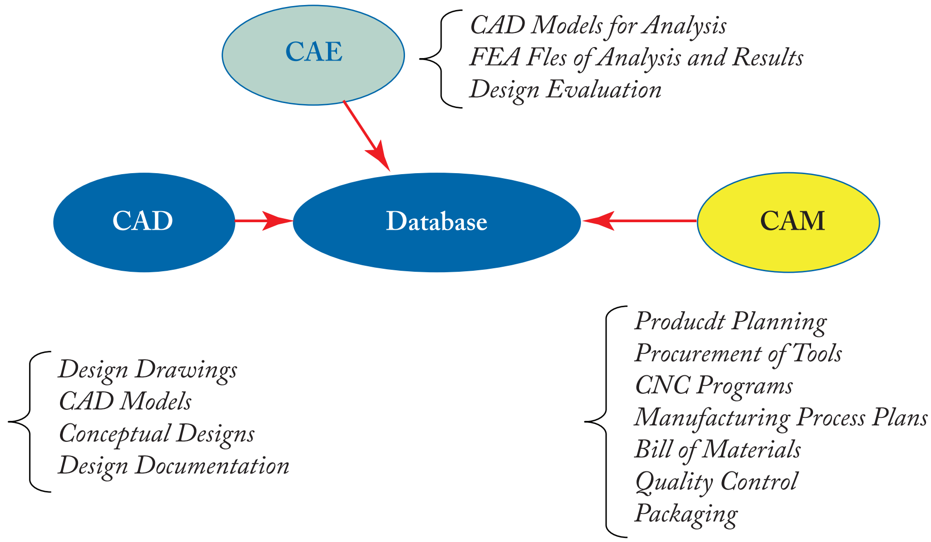


Figure 8.4: Product data management integrating CAD/CAE/CAM through a database.

3. The Market (size, growth, trends, and competition)
4. The Product (description, customer benefit, potential product limitations, present state of the product, manufacturing, warranty)
5. Sales/promotion (marketing plans, product pricing, advertising and promotion)
6. Financials
7. Appendix

More details about each of the elements can be found in business books; for example, see *Anatomy of a Business Plan: A Step-by-Step Guide to Building a Business and Securing Your Company's Future* by Linda Pinson and Jerry Jinnett [21].

8.7 VIRTUAL ENGINEERING

Virtual engineering is a simulation based approach used to help engineers make decisions about real systems by simulating the geometric and physical properties. Virtual engineering extends over the entire product realization process and includes simulation of various engineering activities, the design and manufacturing process, operation, inspection and evaluation. Virtual engineering encompasses a range of engineering activities from simple geometric modeling to simulation of production systems, and building of virtual prototypes or virtual products. Some of the major applications of virtual engineering are listed below.

VIRTUAL DESIGN

Engineering design assisted by visual simulation of product performance provides a creative and intuitive approach to the design process. It is a top-down design approach that takes into account global functional requirements and then proceeds to detailed component designs. Virtual design allows engineers to be more creative and interactively immerse themselves in the conceptual design process. Digital simulation and virtual prototyping allow the development of virtual products that can be assembled even in cases where complete details of the component parts are not available. Design optimization is achieved more effectively with virtual prototyping as compared to the costs and time involved in building physical models.

VIRTUAL MANUFACTURING

Quantitative as well as qualitative assessments of manufacturability can be made with virtual engineering. Quantitative assessments would provide information about such factors as processing times, cycle times, costs, product quality, set up times, run times, and labor costs, while qualitative assessments provide a rating for the ease of manufacturability. Virtual engineering supports both types of manufacturability assessments and assists in identifying, characterizing, and modifying potential quantitative and qualitative design attributes that interfere with manufacturability.

VIRTUAL PROTOTYPING

Virtual prototyping eliminates the need for costly and time consuming methods involved in building physical prototypes. It allows visualization of the assembly of parts in a system through geometric modeling of a virtual prototype. The virtual prototype is also referred to as a digital mockup or digital preassembly. An accurate virtual prototype assists the design engineer in detecting and repairing any design flaws and establishing the feasibility of an assembling operation. Design optimization is gradually achieved through increasingly refined iterations of the virtual prototype until it has the comprehensive characteristics of a physical prototype.

COLLABORATIVE ENGINEERING AND CUSTOMER INTERFACE

Virtual engineering facilitates timely and cost-effective interfacing of information between key stakeholders in the design and product development phases. Digital product information can be shared quickly and cost effectively between engineers, designers, and customers, and this feedback can be used to rapidly develop a quality product. This collaborative process also enhances key relationships in product development between producers, suppliers, and customers for example.

CHAPTER 9

Sample Design Projects

After reading this chapter, you will be able to:

- Better understand and implement the design process
- Carry out the design steps for selected design problems
- Appreciate the effort and fun involved in creating designs to help society

9.1 OVERVIEW

This chapter introduces sample design projects to provide the reader with additional real life examples of product design projects. These sample projects further illustrate how the systematic design process is followed in order to achieve a good design. Several professional organizations (ASME, SAE, NASA, and IAT) conduct annual design competitions to challenge students to test their design and manufacturing skills, and appreciate the team work and fun involved in engineering projects. Two of the projects discussed are based on the annual design competitions hosted by NASA and IAT. A brief list of design projects previously assigned by the author is also presented.

9.2 BENEFITS OF PARTICIPATING IN THE DESIGN COMPETITIONS

Engineering product design competitions provide students with the following learning objectives and outcomes.

- applying the design process starting from concept to final product design
- applying creativity, imagination, and problem solving skills
- working with fellow students on a common goal and learning from others
- finally, acquiring skills in real-world design

9.3 SAMPLE DESIGN PROJECT #1 – DESIGN OF AN AUTOMATIC MUSIC BOOK PAGE TURNER

A student group from IUPUI designed and prototyped an automatic music book page turner and the sequence of design and prototyping steps is presented below.

NEED

Every musician would like to have an automatic music book page turner to leave his/her hands free for playing an instrument.

OBJECTIVE

Design and build an automatic music book page turner which will allow musicians to turn pages of a music book without using their hands.

CUSTOMER AND ENGINEERING REQUIREMENTS

Following a QFD process of the design need, the customer and engineering requirements obtained are presented in Table 9.1.

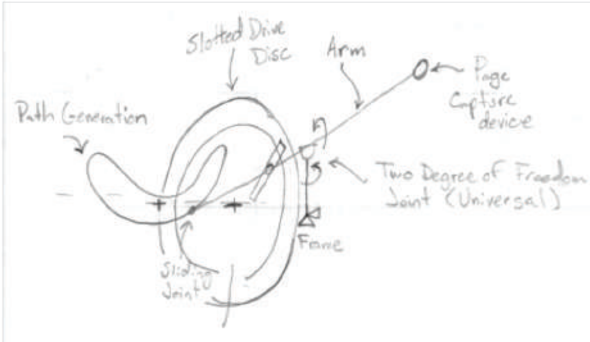
Table 9.1: Customer requirements and engineering specifications

Customer Requirements	Engineering Specifications
Produce very little blocking of page view	Not block view of music page for more than 3 seconds
Operate quietly	Operate at no more than 15 dB
Work with different book types and number of pages	Length and width should be adjustable for different sized music books with a maximum open book size of 17"x 11"
Able to advance pages forwards and reverse	Able to accommodate music books with 5–300 pages and advance pages in the forward and reverse directions with input from the user
Operate on a standard music stand	Sharp edge of the cutting blade can be adjusted for right- or left-handed people
Require little or no maintenance	No regular maintenance from user for lifetime of product
Portable and easy to use	Physical dimensions of the device should be within 25"x15"x4"

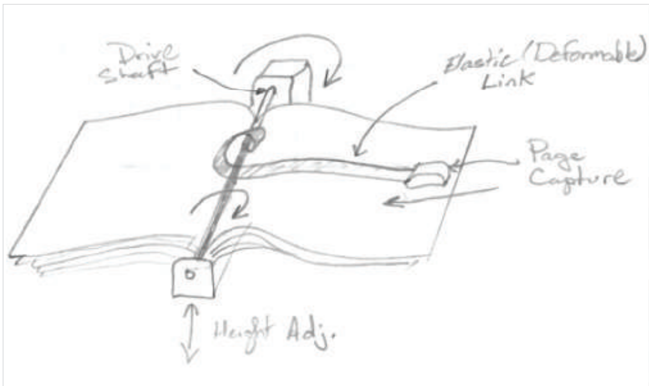
CONCEPTUAL DESIGN AND EVALUATION

The automatic music page turner design team developed three concepts after eliminating the obvious ones. The three concepts generated are shown in Fig. 9.1.

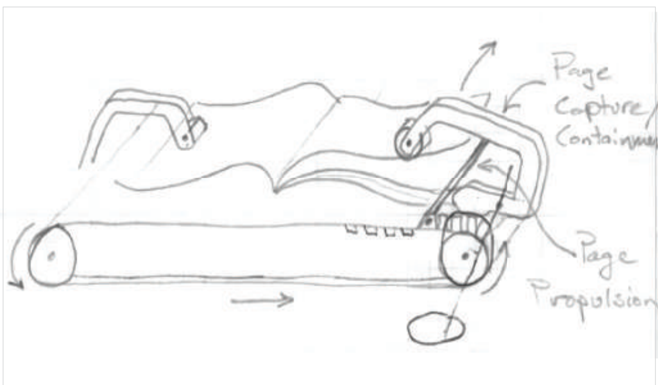
Using the decision matrix method, the automatic music page turner design group identified the candidate concept which is presented in Table 9.2.



Concept I – Mechanized Arm Concept



Concept II – Rotational Deformable Arm Concept



Concept III – Linear Track Concept

Figure 9.1: Conceptual designs generated for the automatic music page turner.

Table 9.2: Concept evaluation of automatic book page turner using the decision matrix method

Criteria	Weight	Mechanized Arm	Linear Track Mechanism	Rotational Deformable Arm
Adjustability	3	Datum	+	+
Height	2		S	S
Width	2		S	S
Thickness	2		S	S
Number of off-shelf parts	2		-	+
Visual interference	3		+	-
Maintenance	2		+	-
Noise Output	3		+	+
Page Progression	3		+	+
Number of Links	2		-	+
Most Developed Concept	1		+	-
Analytical Difficulty	2		+	+
Difficulty in Prototyping	2		+	+
Total Plus			8	7
Total Negative			2	3
Overall Score			15	11

CAD MODELING AND ANALYSIS

The automatic music page turner design teams carried out CAD modeling and design analysis using finite element analysis in order to make sure the stresses are within the limits of material chosen and to identify potential failure modes in the design. Figures 9.2–9.4 show the results of the CAD modeling, assembly, and design analysis.

PROTOTYPING THE FINAL DESIGN CONCEPT

A prototype of the developed automatic music book page turner example is shown in Fig. 9.5.

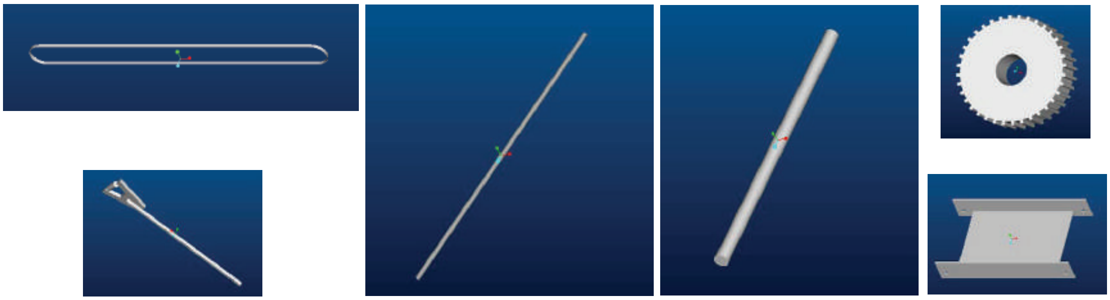


Figure 9.2: CAD modeling of the various components (belt, gear, picker arm, base, push bar, and gear drive bar) of the final design concept for the automatic music page turner example.

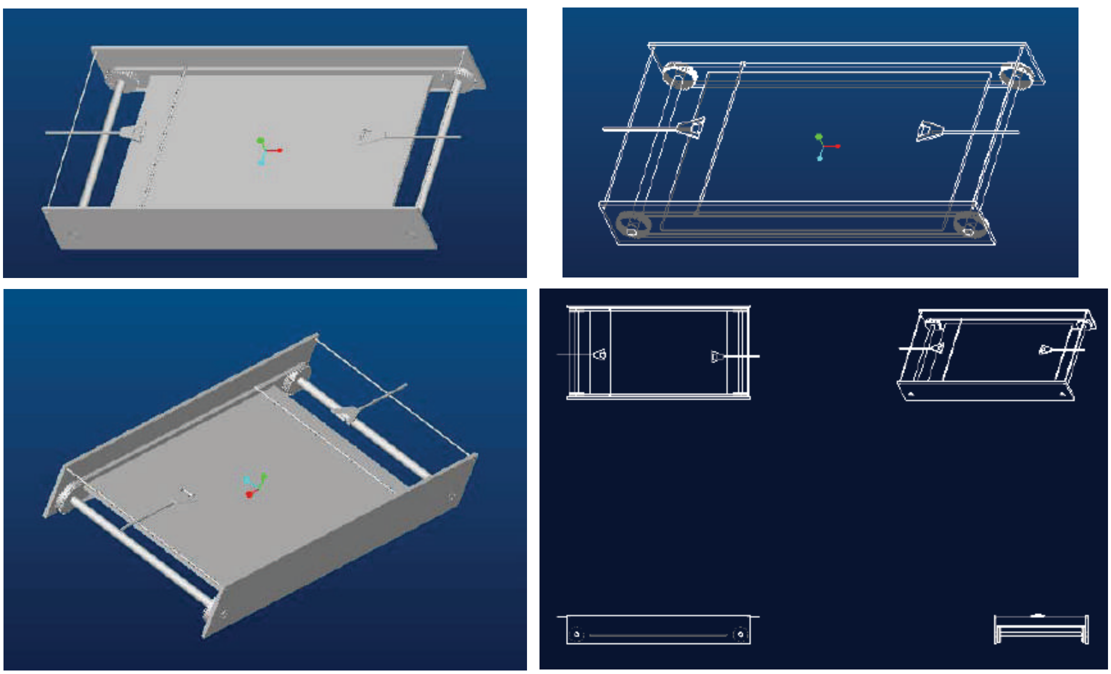


Figure 9.3: CAD assembly of the various components shown different views (solid model, wire frame model, and 2D drawings) for the automatic music page turner example.

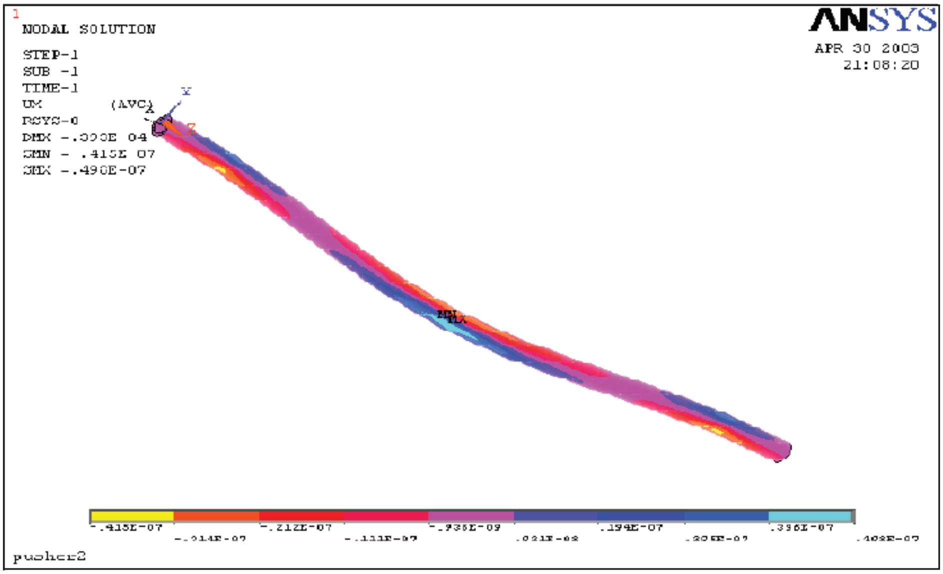


Figure 9.4: CAE analysis of the design concept for the automatic music page turner example.

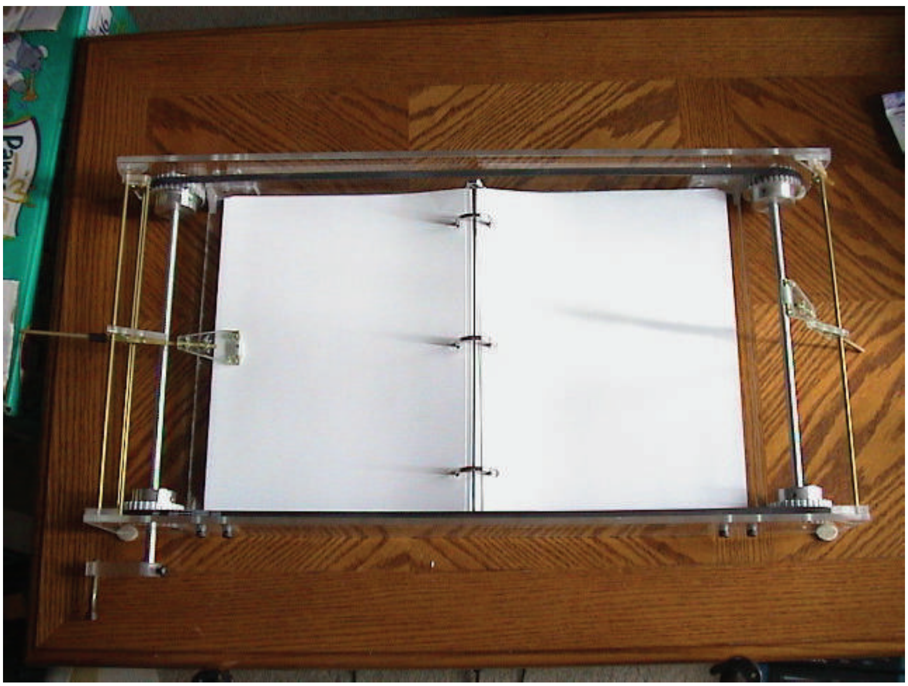


Figure 9.5: A prototype of the final design concept of the automatic music page turner.

EVALUATING THE FINAL DESIGN AGAINST ENGINEERING REQUIREMENTS

The automatic music page turner design team evaluated their design to see if their design met the engineering requirements. Table 9.3 shows the design evaluation of the example of the automatic music page turner.

Table 9.3: Evaluation of final design requirements of the automatic music page turner

Engineering Requirements	Does Design Meet Requirements?
Device should not block view of music page for more than 3 s	Yes
Device should operate at no more than 15 dB	Unknown
Device length and width should be adjustable for different sized music books with a maximum open book size of 17" × 11"	Yes
Device should be able to accommodate music books with 5–300 pages	Yes
Device should be able to advance pages in the forward and reverse directions with input from the user	Yes
Device should be able to operate on a standard music stand	Yes
Device should require no regular maintenance from user for lifetime of product	Yes
The physical dimensions of the device should be within 25" × 15" × 4"	Yes

9.4 SAMPLE DESIGN PROJECT #2 – DESIGN OF AN OBLIQUE FLYING WING

One student group designed and built a remote-controlled oblique flying wing capable of flying under subsonic conditions. The sequence of design and prototyping steps is presented below.

OBJECTIVE

The main objective of this design project is to design and build a controllable subsonic oblique flying wing aircraft. The customers for this project are the individuals who are interested in flying for fun and the manufacturers of remotely controlled aircrafts.

CONCEPTUAL DESIGN

Due to the complexity of the design objective, hand drawings along with the construction of a small simple wooden glider were utilized during the conceptual design phase. The final concept is shown in Fig. 9.6.

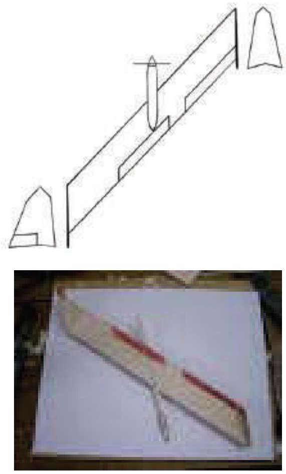


Figure 9.6: Conceptual design of the oblique flying wing.

CAD MODELING AND ANALYSIS

Using the conceptual design, the overall configuration was modeled in a CAD environment. Several modifications were made during the analysis so that the final concept satisfied the design objective. Figure 9.7 shows the CAD model and drawings of the final design concept. Airfoil and plan form analysis were performed with computer simulations to make sure once again that the design objectives were met.

PROTOTYPING AND OPTIMIZATION OF THE FINAL CONCEPT

A simple small scale "technology demonstrator" was manufactured to validate the design concept and further evaluate the design. Based on results from the prototype model and analysis, modifications were made and the final product was designed. Figure 9.8 shows the different views of the prototype model.

FINAL PRODUCT

Figure 9.9 shows the final product after few iterations based on the prototype model and optimization analysis.

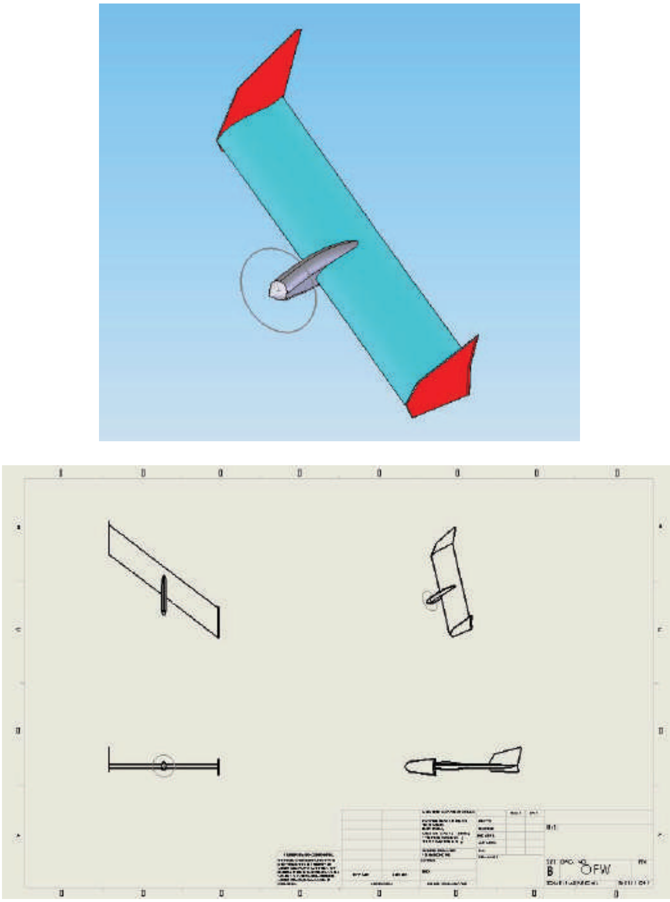


Figure 9.7: CAD model of the final design concept.

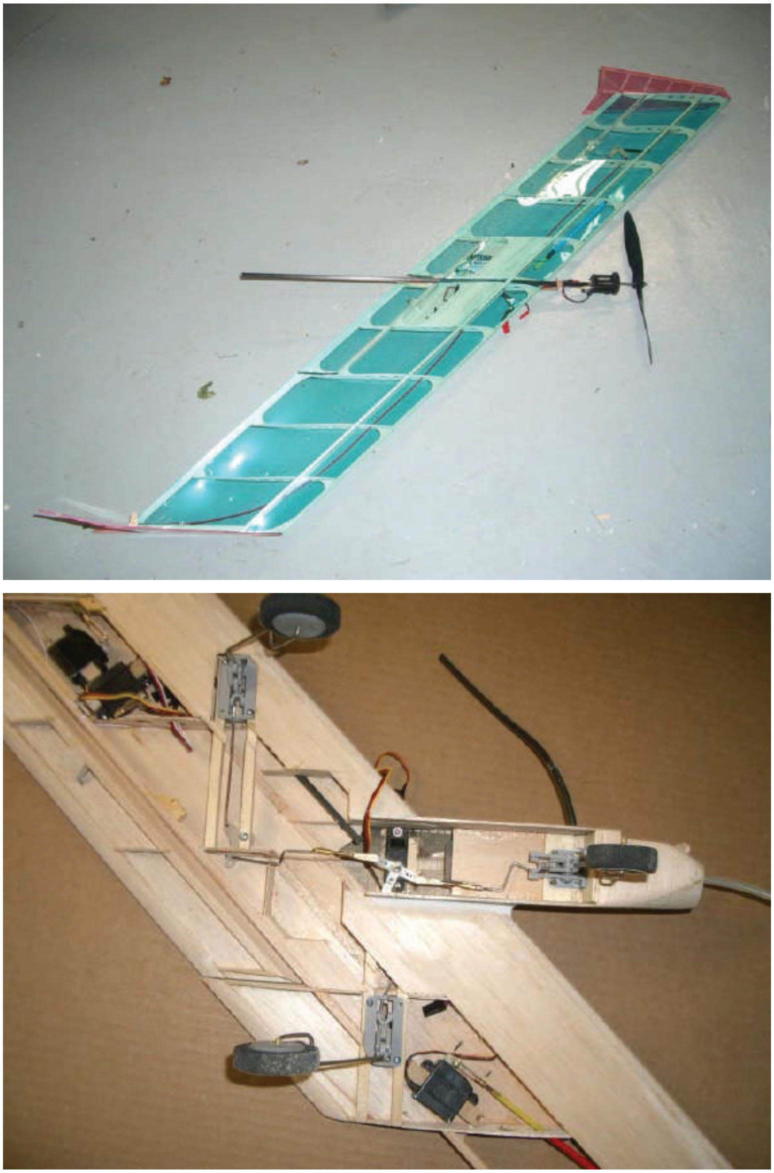


Figure 9.8: Prototype model of the final design concept.

Figure 9.9: Final product of the oblique flying wing aircraft (courtesy of Evan Neblett).

9.5 SAMPLE DESIGN PROJECT #3 – NASA MOONBUGGY DESIGN

The NASA Space and Rocket Center at Huntsville, Alabama has been organizing the Great Moonbuggy Race competition since 1994 to encourage and challenge students to be involved in the design of the moonbuggy vehicle and compete nationally. Students are required to design a vehicle that addresses a series of engineering problems that are similar to problems faced by the original moonbuggy team.

OBJECTIVE

The main objective of this competition is to design, build, and race a human-powered vehicle able to conquer typical obstacles that a moon rover might encounter.

DESIGN SPECIFICATIONS

Design requirements as specified by the rules and regulations of the Great Moonbuggy Race Competition by NASA (`www.nasa.gov/~education`) are as follows:

1. Moonbuggy Teams – Each moonbuggy must be the work of a student team of a high school or an accredited institution of higher learning. A group of high schools may also work in collaboration toward building a moonbuggy entry.

2. Propulsion System – Human-powered (one or two passengers); energy storage devices—such as springs, flywheels, or others—are not allowed.

3. Un-Assembled Dimensions – Prior to course testing, assembly judging is conducted the morning of the race, prior to the first run. The un-assembled vehicle must fit (or be collapsible) to fit in a volume of maximum dimension $4' \times 4'$. A container of this dimension will be placed over the collapsed or un-assembled moonbuggy for verification.

4. Weight – The vehicle must be lifted and carried $20'$by the two passengers, without aid of any sort (e.g., no wheels) in the unassembled $4' \times 4'$volume.

5. Assembled Dimensions – The maximum width of the assembled vehicle is $4'$, including wheels. There are no constraints for height and length of the assembled vehicle.

6. Other than the stated configuration requirements, no constraints are imposed regarding materials and design.

7. Vehicles, or parts of vehicles, not constructed by the entering team are not acceptable. Vehicles that have been previously entered should contain major modifications that attempt to improve on design and performance. Students are expected to build their own buggies, and the course drivers, chosen from each team, must also be builders of the vehicle.

8. No constraints are imposed in the means of contact between the buggy and the simulated lunar surface. We encourage creativity and participants are open to using wheels, belts, treads, etc.

9. No body part of either passenger may be closer than $15''$to the flat surface on which the vehicle is supported.

10. The vehicle must have a turning radius of $20'$or less.

11. For safety reasons, it is recommended that the center of gravity of the "vehicle plus passengers" be low enough to safely handle slopes of 30 degrees forward and sideways. Any moonbuggy exhibiting handling characteristics or other vehicle dynamics that are deemed unsafe or unstable by the judges will be disqualified from the competition. This determination will be made by inspection of the assembled moonbuggies prior to course testing.

12. Each vehicle must have seat restraints for each of the two passengers. The restraints must be worn during runs of the course.

13. All sharp edges and protrusions must be eliminated (i.e., padded) or guarded as necessary to the satisfaction of the judges.

14. The vehicle must be equipped with the following elements: simulated TV camera (approximately 2″× 3″× 6″), simulated high gain antenna (minimum diameter of reflector: 2'), two simulated batteries (each approximately 4″× 6″× 8″), moon dust abatement devices, simulated electronic controls—radio and display console (total combined minimum size 1 cubic foot) and U.S. flag. A university pennant is optional. These items (and their sizes) will be checked prior to, and after, each course run.

15. Backing up is not required, but may be useful.

16. Vehicles that do not satisfy the intent of the moonbuggy competition can be disqualified.

17. Only vehicles registered for the competition will be allowed in the pits area.

Figure 9.10 shows the moonbuggy design by VCU students in Mechanical Engineering that completed the competition.

Figure 9.10: Moonbuggy design by the students of Mechanical Engineering at the Virginia Commonwealth University.

9.6 SAMPLE DESIGN PROJECT #4 – DESIGN OF A LOW-COST AMBULANCE

The Institute for Affordable Transportation (IAT) provides sponsorship for designing vehicles that enable people in rural areas of developing countries to expand their micro-businesses. IAT seeks to promote trade and reduce poverty by creating a low-cost utility vehicle that provides mobility, freedom, and economic hope to people. Basic Utility Vehicles (BUVs) fill the gap between the motorcycle and the automobile.

The Institute for Affordable Transportation (IAT), Indianapolis, Indiana (`www.drivebuv.org`) has been organizing the Basic Utility Vehicle (BUV) Design competition since 2000 to encourage and challenge college students to design, build, and participate in the competition. The basic utility vehicle is intended for use in remote parts of the world to improve standards of living by providing simple, cost effective transportation with all-terrain capabilities. Due to this consideration, the design should be versatile and have an almost unlimited amount of uses. Additional BUV design considerations include designing a product that is compatible with existing production components, is reliable, is gender friendly, has sufficient safety devices, and requires little maintenance. In addition to providing basic transportation, the BUV should be able to carry goods to improve local commerce and productivity of the community. Figure 9.11 shows a low-cost ambulance designed by a group of mechanical engineering students at VCU for use in third world countries using the local resources as well as provides employment in the community.

Figure 9.11: Low-cost ambulance designed by the students of Mechanical Engineering at VCU for use in developing countries.

9.7 EXAMPLE PROJECTS/DESIGN PROBLEMS

The following is a brief list of design projects assigned by the author to his students.

- Design of a foot orthosis
- Design of an electro-mechanical toy
- Design of a showcase to illustrate the Mechanical Engineering discipline
- Stamping machine design for recycling aluminum cans
- Battery thermal management system design
- Pressure-activated sensor design
- Design of an adaptive device to assist a disabled person to shred papers
- Design of a patient conveyer device
- Design of a microkeratome for cornea refractive surgery
- Trephination handle design
- Fault detection system design
- Design of an intelligent microprocessor-based device for faults/defects quantification
- Modular eating aid devices for the disabled
- Pressure activated vibration device for orthotic braces
- Design of a device to visualize the radial artery in infants
- Design of an interactive interface for rhinoceros
- Design of a hysterosalpingography catheter
- Design of an adaptable device to water skis for ventilator dependent quadriplegics
- Redesign of a product based on ASHRAE standards
- Moonbuggy steering/suspension re-design

9.8 POSSIBLE DESIGN PROJECTS

The following is a brief list of possible design projects that can be explored.

1. Look into your community and identify a product/item that needs to be designed or re-designed. You should be creative in identifying a product from everyday life.

2. Design a modular eating aid device that can fit to a person sitting in a wheel chair and help the person eat comfortably. There are millions of disabled people who have limited or no arm movement due to conditions such as cerebral palsy. These people require assistance with eating. Some of the eating aid devices include coffee/pop drinking aid, fork-knife-spoon using aid, etc. Since eating is such a fundamental need for everyone, these devices will help enormously.

3. To show the young children that science and engineering and designing is fun, the Virginia Science Museum is interested in developing an exhibit that illustrates various mechanical elements (links, gears, cams, etc.) and how they can be used to transmit motion. Design a device that places a ball in a basket when a known weight is placed. The initial step is to place a known weight and the final step will lead to placing a ball in a basket. The device should have at least eight steps involving motion transfer among various mechanical elements.

4. Toys can help teach people of all ages—growing babies and young children at different stages of their development, older kids, tweens or teens, and adults. For example, there are many things infants need to know to get around in the world. Select a stage (like infant, toddler, preschooler). Think about the things they need to learn: talking, color recognition, crawling, walking. How will your toy teach them? Your team's creation might also help older students, or even adults learn a subject, or acquire skills that will help them in everyday life.

5. Insects are very capable of agile flight on a small scale (micro- and nano-scale). If a man-made machines can be built that can fly like an insect, it would have important industrial, civil, and military applications. Design a novel mechanism that can produce flapping motion as well as twisting motion, and is light weight and compact. The designed mechanism can be used in micro-air vehicles and can be easily prototyped using rapid prototype machines.

6. Create a sporty toy that gets you off the couch and on your feet! Think of outdoor sports, water sports, and extreme sports. Your mission is to create a toy that would make you want to skip, run, jump, climb, swing, throw, swim, or another way to be active.

7. Your team is working in the product design and engineering department of a small company, which specializes in small electrical consumer products. During the last strategic

meeting, the board of directors recognized the market potential and approved research and development (R&D) funding for a newly designed electric toothbrush. Design an electric toothbrush for kids as well as adults.

8. Musicians must constantly remove a hand from their instrument to turn the pages of a music book. Some paralyzed people also have difficulty turning the pages of a book due to loss of motion in their hands. Design a mechanism to automatically turn pages of a book, one page at a time, in response to a switch operated by foot. The mechanism should be safe and simple to operate, accommodate a wide range of book sizes, and should not damage the book.

9. The objective of the project is to explore the basic design principles the nature was used to create many different systems. Conduct a case study by selecting a natural design and develop engineering design analysis and drawings through the use of design process methodology.

10. The objective of the project is to bring out the parallels and differences between art and engineering. Conduct a case study by selecting an artistic design and engineering design.

11. Use origami design techniques to design a pop-up toy or a book.

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