CHAPTER

# 1 ENGINEERING DESIGN



## INTRODUCTION

Design is the central activity of the engineering profession. ***Engineering design*** can be defined as a set of decision-making processes and activities that are used to determine the form of a product, component, system, or process, given the functions desired by the customer.[1] The term ***function*** refers to the behavior of the design, that is, what does the design need to do? ***Form***, on the other hand, has to do with the appearance of the design. A product's form refers to its size, shape, and configuration, as well as the materials and manufacturing processes used to produce it.

Engineering design is a part of the larger ***product realization process***. As we see in Figure 1-1, product realization starts with a customer need and ends with a finished product that satisfies this need. The product realization process consists of design and manufacturing processes that are used to convert information, materials, and energy into a completed product. The stages of the product realization process include sales and marketing, industrial design, engineering design, production design, manufacturing, distribution, service, and disposal. ***Product development*** refers to the first stages of the product realization process up to manufacturing. Product development includes engineering design, as well as sales/marketing, industrial design, and production design.

## ASPECTS OF ENGINEERING DESIGN

Our notion of engineering design encompasses many different aspects. For instance, it is a ***process***, one that prominently involves both ***problem-solving*** and ***decision-making*** activities. Engineering design also employs both ***analysis*** and ***synthesis***. By nature it is ***interdisciplinary*** and ***iterative***. Even prior to the emergence of such modern concepts as ***concurrent engineering*** and the design team, there has always been a strong ***social*** aspect to engineering design. Finally, in keeping with the main topic of this book, engineering design is characterized by strong ***graphical*** elements.

Engineering design is really about solving problems. In fact, a simple definition of engineering design is "a structured problem-solving approach."[2] Concisely described, the design process is no more than identifying a problem, carefully researching and defining the problem in order to better understand it, creatively generating possible alternative solutions to address the problem, evaluating these candidate solutions

[1] Rudolph J. Eggert, *Engineering Design*, Pearson Prentice Hall, 2005.

[2] Arvid Eide et al., *Engineering Fundamentals and Problem Solving*, McGraw-Hill, 1997.

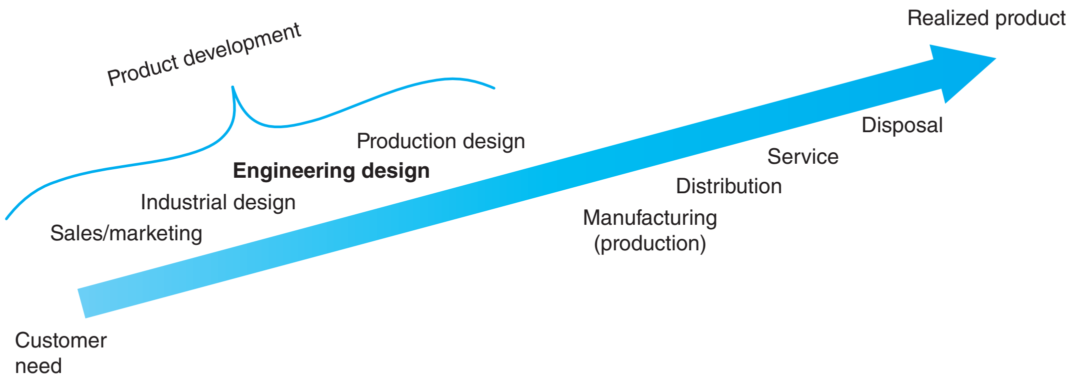



**Figure 1-1** Product realization process (Eggert, Rudolph, J., *Engineering Design, 2nd Edition*, © 2010, Page 12. Reprinted by permission of High Peak Press, Meridian, ID)

to ensure their feasibility, making a rational decision, and then implementing it. One of the hidden merits of an engineering education is that this problem-solving framework becomes so ingrained that it can easily be adapted to deal with life's many problems, technical or otherwise.

Although the need to make decisions is apparent throughout the course of a design's evolution, decision making in conjunction with engineering design typically refers to that part of the design process where competing feasible solutions are evaluated and an optimal solution is decided upon. Because of the numerous ***tradeoffs*** involved, these types of decisions are often difficult to make. Examples of such tradeoffs include strength versus weight, cost versus performance, and towing power versus free-running speed. Optimizing one criterion often means sacrificing the optimum position of the other criterion. Decision making is still something of an art, requiring solid information, good advice, considerable experience, and sound judgment. In recent decades, however, a mathematically based ***decision theory*** has been developed, and it is commonly used in the development of commercial products.

Synthesis is the process of combining different ideas, influences, or objects into a new unified whole. From this perspective, engineering design can be viewed as a synthesis technique, one used for creating new products based on customer needs. More specifically, synthesis refers to creative approaches used to generate potential solutions to a design problem.

Analysis, on the other hand, is the process of breaking a problem down into distinct components in order to better understand it. From the perspective of engineering design, analysis often refers to the tools used to predict the behavior and performance of potential solutions to a design problem.

Good design requires both divergent thinking (i.e., synthesis), which is used to expand the design space, and convergent thinking (i.e., analysis), which is used to narrow the design space by focusing on finding the best alternatives in order to converge to an optimal solution. Chapter 2 includes a section on divergent and convergent questioning.

As a synthetic process, engineering design is interdisciplinary in nature. Although it relies heavily on basic science, mathematics, and the engineering sciences, engineering design still retains its artistic roots. Eugene Ferguson, in his book *Engineering and the Mind's Eye*, notes that "many of the cumulative decisions that establish a product's design are not based in science." He points out that even though design engineers certainly make decisions based on analytical calculations, many important design decisions are based on engineering intuition, a sense of fitness, and personal preference.[3] Chapter 2 discusses the artistic roots of engineering design in detail.

[3] Eugene Ferguson, *Engineering and the Mind's Eye*, MIT Press, 1997.

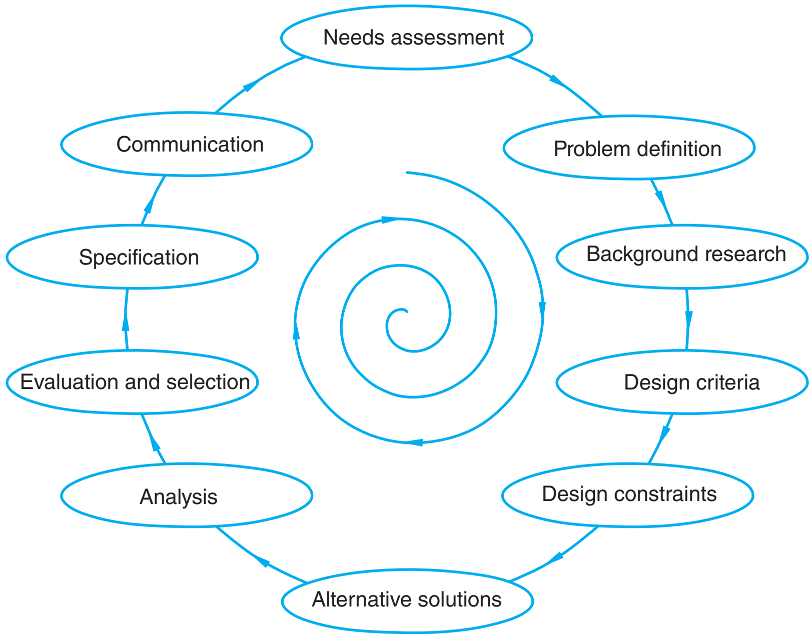



**Figure 1-2** Engineering design process

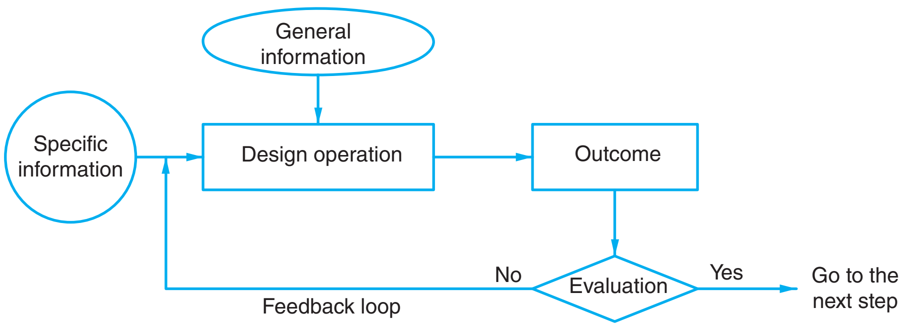



**Figure 1-3** Design process feedback loop (Based on [4])

An important element of engineering design is communication. It is often noted that a significant portion of an engineer's time is spent in communication (oral, written, listening) with others. Add to this the fact that modern engineering design draws on decision making, optimization, engineering economy, planning, applied statistics, materials selection and processing, and manufacturing, and the interdisciplinary nature of engineering design should be clear.

Although engineering design is frequently described as a sequential process that moves from one stage to the next, it can also be portrayed as a design spiral, where each stage is visited more than once (see Figure 1-2). In any case, feedback loops, like that shown in Figure 1-3,[4] are built into each step in the design process. Based on the latest information, it is often necessary to iterate the various design process steps.

As we have already mentioned, the actual engineering design process is not nearly as structured as that described in engineering design textbooks. There has always been a

[4] George Dieter, *Engineering Design: A Materials and Processing Approach*, McGraw-Hill, 1991.

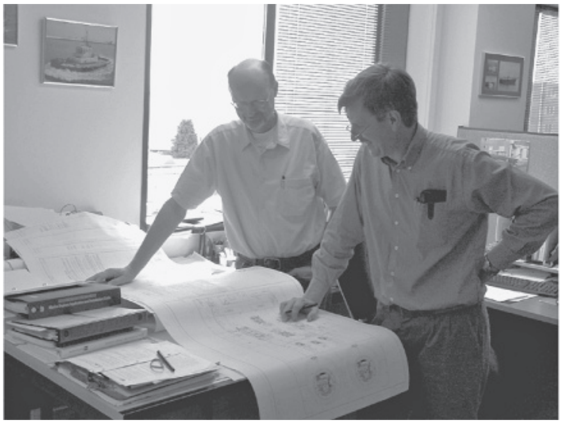


**Figure 1-4** Engineers discussing a design project (Courtesy of Jensen Maritime Consultants, Inc.)

strong social aspect to the design process, perhaps best captured in the notion of the napkin or back-of-the envelope sketch.[5] In fact, a reasonable definition of the engineering design process is "a social process that identifies a need, defines a problem, and specifies a plan that enables others to manufacture the solutions."[6] This social aspect of engineering design is further reinforced by the emphasis in the recent decades on project design teams. Figure 1-4 shows two engineers holding a discussion over an engineering drawing.

Graphics is used throughout the entire engineering design process. Freehand sketching is useful both for generating ideas and for communicating them. Computer-aided design (CAD) is used not only for traditional documentation purposes but also to evaluate design alternatives. Parametric solid models capture design geometry, but they also serve as digital prototypes used in downstream analysis, prototyping, and manufacturing applications, as well as for marketing and sales. This digital prototype is in fact a 3D CAD relational database representing all aspects of the product's design.

[5] For example, the original concept for the Seattle Space Needle was sketched on a placemat in a Seattle coffee house.

[6] Karl Smith, *Project Management and Teamwork*, McGraw-Hill, 2000.

## ANALYSIS AND DESIGN

The undergraduate engineering curriculum includes both analysis and design content. Engineering analysis uses science, mathematics, and computational tools to predict the behavior of an engineering design. Analysis is characterized by breaking a complex problem up into manageable pieces. Analysis attempts to simplify the real world by using models. In a typical analysis problem, the input data are given, and there is a single solution to the problem.

Design problems employ synthesis as well as analysis. Design problems are open-ended; that is, there is more than one solution. In a design problem the correct answer is unknown. For this reason, optimization and decision-making techniques are often employed in association with design. Design problems are typically constrained by time, money, and legal issues; they tend to be multidisciplinary and of undefined scope.

## PRODUCT ANATOMY

A ***product*** is a designed object or artifact that is purchased and used as a unit.[7] Products vary in complexity depending on the number, type, and function of their components. A ***component*** is either a part or a subassembly. A ***part*** is a piece that requires no assembly, whereas an ***assembly*** is a collection of two or more parts. A ***subassembly*** is an assembly that is included in another assembly or subassembly. For example, a bicycle is a product that can also be thought of as an assembly composed of subassemblies and parts. A rear hub is a subassembly on a bicycle, whereas a handlebar is a part on a bicycle. Both the hub and the handlebar are bicycle components.

## DESIGN PHASES

Product design projects, as conducted by large manufacturing companies like Boeing or Motorola, pass through several distinct phases. See Figure 1-5. In the ***formulation*** phase information

[7] John Dixon and Corrado Poli, *Engineering Design and Design for Manufacturing: A Structured Approach*, Field Stone Publishing, 1999.

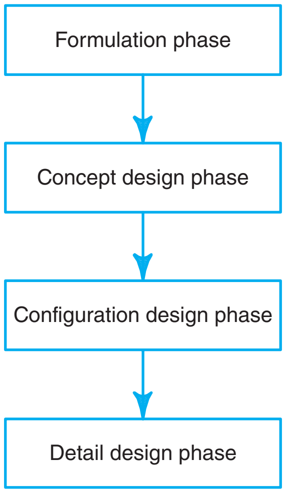



**Figure 1-5** Engineering design phases

is gathered in order to fully understand the design problem. Next, functional (customer, company) requirements of the product as well as constraints and evaluation criteria are identified; finally, engineering performance targets are developed. In the ***concept design*** phase the product is decomposed initially by component (form) and then by function in order to better understand it. Concept alternatives are next generated to meet each product subfunction; these subfunction alternative concepts are then analyzed to determine their feasibility, and finally, they are evaluated on the basis of the evaluation criteria. The concept design phase concludes with the selection of the best concept alternatives for each product subfunction. By the conclusion of the ***configuration design*** phase, the type and number of components of the product, their arrangement, and their relative dimensions have been determined. In the ***detail design*** phase, a package of information that includes drawings and specifications sufficient to manufacture the product is prepared.

## DESIGN PROCESS OVERVIEW

The design phases describe the actual procedure employed by a manufacturing company to bring new products to market. The engineering design process, on the other hand, is more an instructional framework used to describe the idealized steps taken by an engineering team in developing a design.

The engineering design literature includes many different versions of this process, each with a different number of stages, or steps. The design process template (see Figure 1-2) employed in this work[8] includes (1) needs assessment, where specific needs (problems) are identified, (2) problem definition, where the problem is clarified, (3) background research, where research is conducted to gather additional information about the problem, (4) design criteria, where desirable characteristics of the design are identified, (5) design constraints, where quantitative boundaries that limit the possible solutions to the problem are identified, (6) alternative solutions, where candidate solutions are conceptualized and generated, (7) analysis, where the alternative solutions are analyzed in an effort to determine their feasibility, (8) evaluation and selection, where the remaining solutions are evaluated with respect to a weighted criteria and the best candidate is selected, (9) specification, where drawings and technical specifications documenting the design are created, and (10) communication, where written reports and oral presentations describing the design are developed. Many of the steps (e.g., problem definition) may be revisited multiple times as additional information comes to light. Further, the stages may not necessarily be performed in the order specified here, and some steps may be omitted entirely.

It is worth noting that the pace in an engineering design office is driven by the available billable hours. Engineering design is tightly constrained by the time available to get the job done. If the billable hours are limited (and they always are), then tough decisions must be made, and some of the idealized steps described here are abbreviated— or even eliminated.

## NEEDS ASSESSMENT

The engineering design process starts with the recognition of a need that can potentially be satisfied using technology. In many cases, needs are

[8] Adapted from Eide.

identified not by engineers but rather by actual users, sometimes with the assistance of experts. See Chapter 2 for additional information on the user's role in the design process. Potential clients may also approach design firms with a specific need. In a large manufacturing company, the sales or marketing department maintains contact with its customer base and identifies many of these needs. In a more systematic approach, product ideas are generated by a product planning group.

Needs arise for a variety of reasons, including (1) a product redesign in order to make it more profitable or effective, (2) the establishment of a new product line, (3) a need to protect public health and safety or to improve quality of life, (4) an invention, often by an individual, that is then commercialized, (5) opportunities created by new technology or scientific advances, and (6) a change in rules, requirements, or the like. The outcome of the needs assessment is a list of needs or requirements, which then becomes a part of the problem definition.

## PROBLEM DEFINITION

Once a list of needs has been developed, the next step in the design process is to clearly and carefully formulate the problem to be solved. At first glance this step may seem somewhat trivial, but the true nature of the problem is not always obvious. A poorly defined problem can lead to a solution search that is either misdirected or too limited in scope. A good problem definition should focus on the desired functional behavior of the solution, rather than on a specific solution. For example, if the issue is lawn maintenance, then "Design a better lawn mower" presupposes the solution. If the problem is restated as "Design an effective means of maintaining lawns," then the options are kept open.[9] When the problem is defined as broadly as possible, novel or unconventional solutions are less likely to be overlooked. Another tip when formulating a problem is to focus on the source of the problem, rather than on the symptoms. In any event, a complete definition of the problem should include a formal ***problem statement***.

A problem statement attempts to capture the essence of a problem in one or two sentences. A problem is characterized by three components: (1) an undesirable initial state, (2) a desired goal state, and (3) obstacles that impede efforts to go from the undesired to the desired state.[10] A good initial problem statement should consequently describe the nature of the problem, as well as express what the design is intended to accomplish. In further iterations, the obstacles that prevent reaching the desired state may also be included.

## BACKGROUND RESEARCH

The problem having been broadly defined, the next step in the engineering design process is research. Background research is conducted in order to obtain a deeper understanding of the problem. Information is sought regarding the target user, the intended operating environment, additional constraints that bound the solution, prior design solutions, and so on. Useful questions that may be posed at this stage include: What has been written on the topic? What must the design do? What features or attributes should the solution have? Is something already on the market that may solve the problem? What is right or wrong with how it is being done? Who markets the current solution, how much does it cost, and how can it be improved upon? Will people pay for a better one if it costs more?

Common sources include existing solutions, the library, the Internet, trade journals, government documents, professional organizations, vendor catalogues, and experts in the field. Regarding existing solutions, ***reverse engineering*** is the process of physically disassembling an existing product to learn how each component contributes to the product's overall performance. Manufacturing companies use reverse engineering techniques to gain insight into a competitor's design solutions. Applied systematically, ***best-in-class*** solutions can then be identified for a broad range of

[9] Restating the problem in this way led to the invention of the Weed Eater® lawn trimmer.

[10] G. Pahl and W. Beitz, *Engineering Design: A Systematic Approach*, Springer-Verlag London, 1996.

**Table 1-1 Tugboat design criteria**

| Specific | General |
|---|---|
| Bollard pull (thrust, towing power) | Appearance |
| Habitability | Cost |
| Maneuverability | Durability |
| Seakeeping | Ease of maintenance |
| Speed (free-running) | Ease of operation |
| Stability (safety) | Environmental protection |
| Stable work platform | Reliability |
| Visibility from the pilothouse | Use of standard components |
| Workmanship | |


**Figure 1-6** Tugboat photograph (Courtesy of Jensen Maritime Consultants, Inc.)

common engineering problems. Reverse engineering is discussed further in Chapters 3 and 14.

## DESIGN CRITERIA

Design criteria[11] describe desirable characteristics of the solution. They tend to originate from experience, research, marketing studies, customer preferences, and client needs. Design criteria are used at a later stage in the design process to qualitatively judge alternative design solutions. Design criteria may be categorized as either general or specific. General criteria categories applicable to most all design projects include cost, safety, environmental protection, public acceptance, reliability, performance, ease of operation, ease of maintenance, use of standard components, appearance, compatibility, durability, and so on. Criteria categories specific to a certain design might include weight, size, shape, power, physical requirements for use, reaction time required for operation, and noise level. Table 1-1 provides examples of both general and specific criteria for a tugboat design similar to that shown in Figure 1-6.

## DESIGN CONSTRAINTS

Design constraints limit the possible number of solutions to a given design problem. Design constraints are quantitative boundaries associated with each design objective. They establish maximum, minimum, or permissible ranges for physical or operational properties of the design, environmental conditions affecting the design or impacting the environment, and ergonomic requirements, as well as economic or legal constraints. A feasible design solution must satisfy all of the design constraints.

Design constraint categories include (1) *physical*—space, weight, material, etc., (2) *functional or operational*—vibration limits, operating times, speed, etc., (3) *environmental*—temperature ranges, noise limits, effect on other people, (4) *economic*—cost of existing competitive solutions in the marketplace, (5) *legal*—governmental and other regulations, and (6) *ergonomic* (or human) factors—strength, intelligence, anatomical dimensions, etc. Some design constraints, organized by category, for a tugboat are shown in Table 1-2.

## ALTERNATIVE SOLUTIONS

Having thoroughly researched the problem, the next step is to systematically generate as many alternative product solutions as possible for subsequent analysis, evaluation, and selection. The group technique most commonly used for generating ideas is ***brainstorming***. The objective of brainstorming is to develop as many ideas as possible in a limited amount of time. Roughly an hour

[11] In engineering design literature, design criteria are frequently expressed as design objectives or as design goals.

**Table 1-2 Tugboat design constraints (sample)**

| | |
|---|---|
| **Physical** | **Environmental** |
| ASTM A-36 steel used for hull | Engine room noise level < 120 decibels |
| Fresh water > 6,000 gallons | |
| Fuel > 30,000 gallons | **Legal (Regulatory Bodies)** |
| Heel less than $\frac{1}{4}$ degree | American Bureau of Shipping (ABS) |
| Length Overall (LOA) < 100' | American Society of Mechanical Engineers (ASME) |
| Railing height > 39 inches | American Society for Testing and Materials (ASTM) |
| | Environmental Protection Agency (EPA) |
| **Functional/Operational** | International Maritime Organization (IMO) |
| Accommodations for 6 crew | Occupational Safety and Health Administration (OSHA) |
| Bollard pull > 30 tons | |
| Horsepower > 2500 BHP | **Ergonomic** |
| Running speed > 12 knots | Accommodations headroom > 6 feet |
| | |
| **Economic** | |
| Cost < $8 million | |

is typically allotted for a brainstorming session. Emphasis is placed on the quantity, rather than the quality, of the ideas. Free expression is essential; the ideas can be evaluated later. Upon occasion, one group member's seemingly impractical notion serves as the inspiration for a teammate's more viable idea. It is important that all group members participate as equals. A group leader can start with a clear statement of the problem, invite ideas regarding the solution, and set the pace of the session. Using marker pens and large Post-it notes (or rolls of butcher paper), the ideas should be recorded for all of the participants to see. Brainstorming is discussed further in Chapter 2.

As we discussed in the section on product anatomy, a product is composed of different components. Each component has its own form, as does the product. Similarly, a product has a primary function, but it also has secondary functions, or subfunctions. For example, the primary function of a coffee maker is to make coffee, but it also needs to store ground coffee and water, hold a filter, brew coffee, convert electricity to heat, and keep the coffee pot warm. To ensure a robust design, multiple concept alternatives need to be generated for each product subfunction.

A ***morphological chart*** is a tool that can be used to expand the number of concept alternatives. Product subfunctions are listed versus concept alternatives in a table. Subfunctions are listed vertically, in a column, and the corresponding concept alternatives horizontally, in a row. Table 1-3

**Table 1-3 Morphological chart for a portable water filter**

| Function | Solution 1 | Solution 2 | Solution 3 | Solution 4 | Solution 5 |
|---|---|---|---|---|---|
| draw water | manual | hose | hose w/ float | hose w/ float, prefilter | |
| move water | hand pump | lever pump | gear pump | dual piston pump | gravity feed |
| filter water | ceramic | ceramic w/ carbon core | fiberglass | labyrinth | iodine resin |
| collect water | manual | threaded adaptor base | built-in collection bottle | | |

shows a morphological chart for a portable water filter. With this technique, a vast number of possible solutions can be identified. Although some of these solutions may be incompatible, morphological analysis is nonetheless useful in identifying a great many combinations, some of which may be unusual or innovative.

In order to compete globally, large manufacturing companies engaged in product realization systematically optimize a product's design at the subfunction level. For first-year student design projects, though, it may be sufficient to generate, evaluate, and then select from product level alternative solutions. For example, each member of the design team may propose an alternative solution to the problem, as shown in Figure 1-7.

Many designs, too, have distinct solutions that have developed over time. Drawbridges, for example, include single and twin span bascule, vertical lift, and rotating solutions (see Figure 1-8), each one serving as an alternative solution to the drawbridge problem.

Students may well come up with their own innovative solutions to these time-honored alternatives, as seen in the student drawbridge concept design solution shown in Figure 1-9.

## ANALYSIS

The concept alternatives generated in the previous stage must be analyzed and then evaluated in order to determine which concepts are worth pursuing. It is possible that some of the candidate concepts that have been generated thus far are not feasible. Design analysis, which uses mathematical and engineering principles to evaluate the performance of a solution, may be used to verify the functionality and manufacturability of the concept alternatives. The objective is to eliminate any infeasible solutions. Although the candidates are at this point no more than abstract concepts, still it may be possible to eliminate some of them by using back-of-the-envelope calculations, investigating their manufacturability, and the like.

## EVALUATION AND SELECTION

After analysis, the remaining feasible candidate concepts are evaluated. Design evaluation

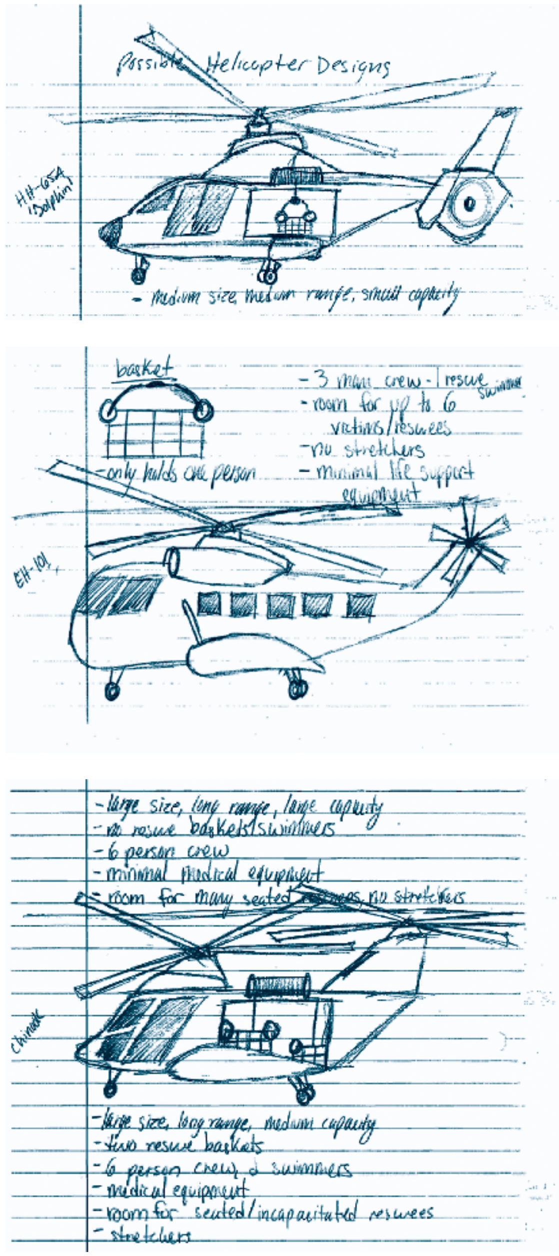



**Figure 1-7** Alternative solution sketches (Courtesy of Matthew Patton)

is a stage in the design process when results from analyses are assessed to determine which alternative is best. The alternatives are evaluated with respect to weighted evaluation criteria. The evaluation criteria are derived from the

(400tmax/iStock/Getty Images)

(Lee Foster / Alamy stock photo)

(ntzolov/E+/Getty Images)

(Potifor/Shutterstock.com)

**Figure 1-8** Drawbridge alternative solutions

design criteria established earlier in the design process, although these criteria may have been modified and further refined based on knowledge gained in the course of the design's development.

It is the responsibility of the design team to come to a decision regarding the relative importance of the different criteria. The evaluation criteria are then weighted in terms of their assigned importance. It is customary to have the criteria weights add up to 100. Once the weighting has been established, the concept alternatives (or product subfunctions) can be evaluated with respect to the weighted criteria. Table 1-4 provides an example of the evaluation procedure used by a student group in a first-year engineering design graphics course to design a dune buggy. An image of the resulting dune buggy concept design appears in Figure 1-10.

**Figure 1-9** Innovative student drawbridge design solution (Courtesy of Yang Cui, Allison Dale, David Shier, Michael Marcinowski)

**Table 1-4 Alternative design evaluation process**

**Weighted Design Criteria**

| | |
|---|---|
| Cost | 30% |
| Safety | 10% |
| Weight and Power | 15% |
| Durability | 15% |
| Ease of Operation | 20% |
| Simple Construction | 10% |

**Alternative Design Rankings (1–10)**

| Weighted Design Criteria | Brian A's Drawing | Dan's Drawing | John's Drawing | Brian S's Drawing | Nilay's Drawing |
|---|---|---|---|---|---|
| Cost | 8 | 10 | 9 | 8 | 8 |
| Safety | 7 | 8 | 6 | 9 | 10 |
| Weight and Power | 10 | 6 | 9 | 10 | 7 |
| Durability | 8 | 7 | 7 | 9 | 8 |
| Ease of Operation | 7 | 10 | 9 | 6 | 9 |
| Simple Construction | 9 | 7 | 6 | 8 | 8 |

**Alternative Design Results (Rankings Multiplied by Percentages)**

| Weighted Design Criteria | Brian A's Drawing | Dan's Drawing | John's Drawing | Brian S's Drawing | Nilay's Drawing |
|---|---|---|---|---|---|
| Cost | 2.4 | 3 | 2.7 | 2.4 | 2.4 |
| Safety | 0.7 | 0.8 | 0.6 | 0.9 | 1 |
| Weight and Power | 1.5 | 0.9 | 1.35 | 1.5 | 1.05 |
| Durability | 1.2 | 1.05 | 1.05 | 1.35 | 1.2 |
| Ease of Operation | 1.4 | 2 | 1.8 | 1.2 | 1.8 |
| Simple Construction | 0.9 | 0.7 | 0.6 | 0.8 | 0.8 |
| Total | **8.1** | **8.45** | **8.1** | **8.15** | **8.25** |

Another example is provided in Figure 1-11. In this industry sponsored project, a senior design team was asked to develop a new and improved endcap display to be used in grocery and other stores. In an effort to evaluate different concepts with respect to the design criteria, the group developed the evaluation matrix shown in Figure 1-11. Each column in Figure 1-11 shows a different endcap criterion.

These include modularity, adjustable shelving, mobility, futuristic design, ease of cleaning, beverage advancement, packout, and header. In the cells beneath each column, images illustrating different ways to satisfy each specific criterion are

**Figure 1-10** Concept dune buggy design (Courtesy of Dan Fey, Nilay Patel, Jack Streinman, Brian Aggen, Brian Shea)

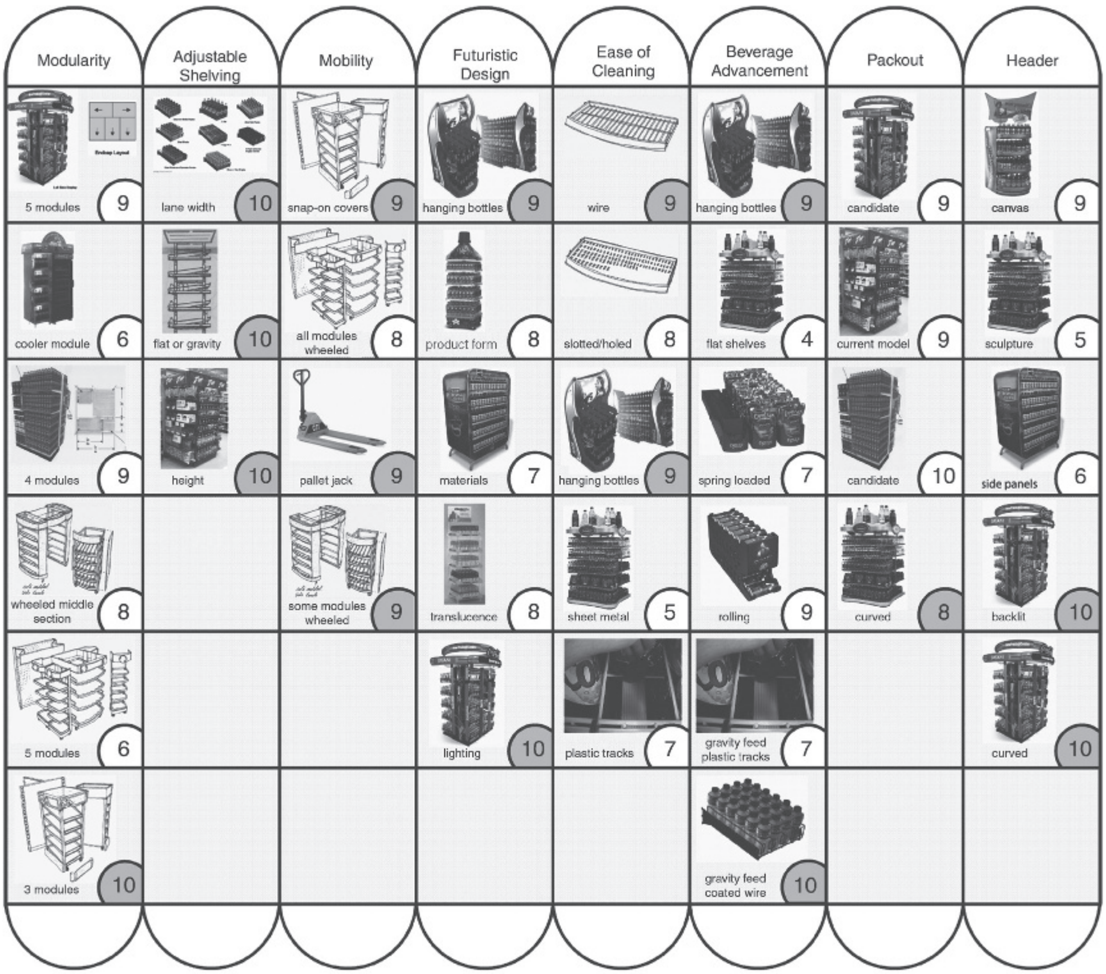



**Figure 1-11** Evaluation matrix for an endcap display (Courtesy of Franklin Wire and Display; Jennifer Bessette, Michelle Wentzler, Madison Major, Faye Hellman)

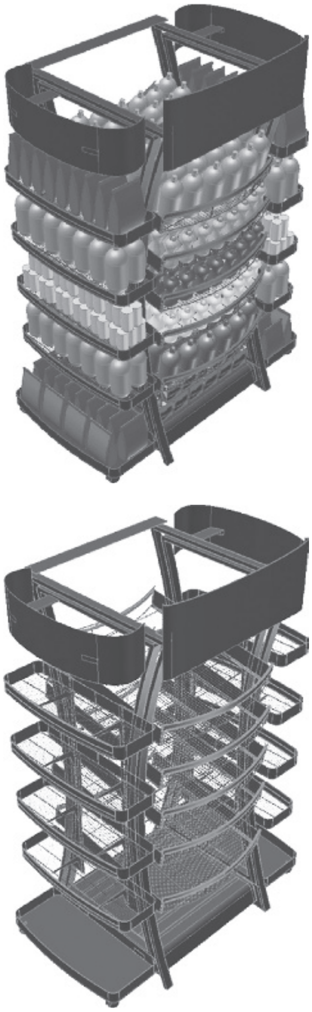


**Figure 1-12** Endcap display design (Courtesy of Franklin Wire and Display; Jennifer Bessette, Michelle Wentzler, Madison Major, Faye Hellman)

shown. Also included in each cell is a rating (the circled number in the lower right-hand corner) assigned by the design team. This rating is used to indicate the performance of the particular solution in meeting the criterion. Using this and other techniques, the design team produced the endcap design shown in Figure 1-12.

## SPECIFICATION

Having selected the best concept alternatives, or simply the best alternative solution, the different product features, parts, and components are configured and arranged using computer-aided design (CAD). ***Configuration design*** refers to that part of product development where planners determine the number and type of components, parts, or geometric features; how they are spatially arranged or interconnected; and the approximate relative dimensions of the components, parts, and features.

This is typically accomplished using a general arrangement or layout drawing. Figure 1-13 shows general arrangement and outboard profile drawings for a 96′ tugboat. The tug design employs two rudder propellers mounted at the stern of the vessel. The rudder propellers can be fully rotated through 360 degrees, independently of one another, giving the vessel exceptional maneuverability and propulsion characteristics.

In addition to the general arrangement drawing, a written specifications document is typically produced at this time. A dictionary definition of ***specification*** is "a detailed description of a particular thing, especially one detailed enough to provide somebody with the information needed to make that thing." The design specification document is consequently a comprehensive description of the product, including the intended uses, physical dimensions, materials employed, operating conditions, and performance targets, as well as the functional, maintenance, testing, and delivery requirements for the designed object. Relevant codes and regulations to be adhered to in the course of the product's design and manufacture are also spelled out in these specifications. Figure 1-14 shows an excerpt taken from the written specifications developed for the tugboat shown in Figure 1-13.

These drawings and specifications may then be used in a formal bidding process called a Request for Proposals (RFP). The drawing package would be sent out to different contractors, in this case shipyards, to be competitively bid upon for the right to construct the vessel. Assuming that the RFP process is successful and an agreement is reached to continue the product's development,[12] the project would then move from the configuration to the

[12] In a manufacturing firm, the decision whether to continue the product's development beyond the configuration design phase would be made internally.

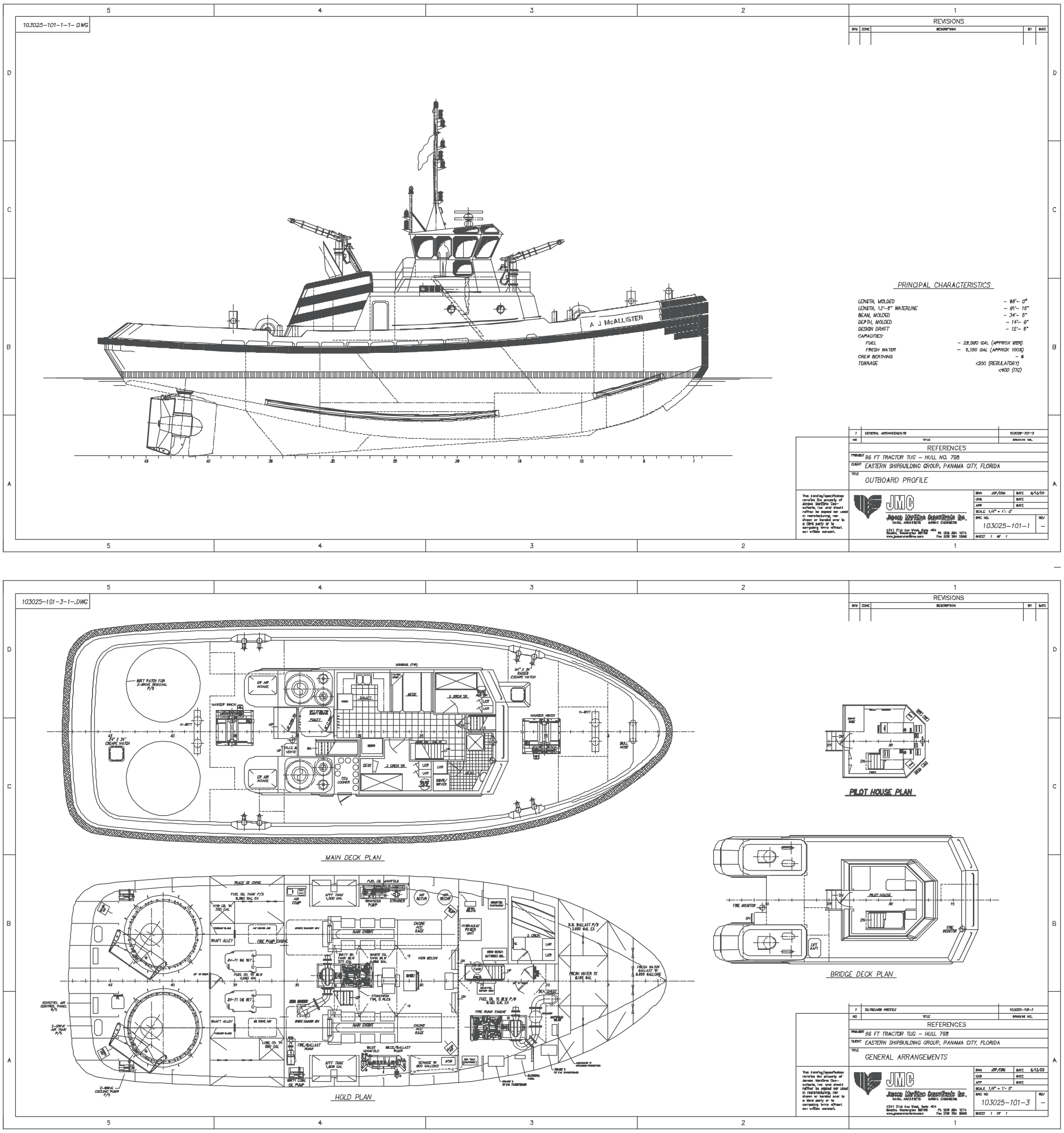



**Figure 1-13** Tugboat outboard profile and general arrangement drawings (Courtesy of Jensen Maritime Consultants, Inc.)

***detail design*** phase. The outcome of the detail design phase is a complete package of information, including many more drawings and more detailed written specifications, sufficient to enable the contractor to fabricate the product.

These ***working drawings*** are also called production or detail drawings. Working drawings are discussed in Chapter 12. They typically include part detail drawings, assembly drawings (see Figure 1-15), and a bill of materials (BOM),

**GROUP 100—HULL STRUCTURE**

***SECTION 101—GENERAL INFORMATION***

See Section 012 for OWNER furnished equipment.

The CONTRACTOR shall design and construct the principal hull structure as described herein. The hull and deckhouse is constructed of steel. All plating shall be ABS Grade A and/or ASTM A-36. All steel shall be wheel-abrated and pre-primed. Steel Certificates shall be provided to the OWNER, along with location of the certified steel.

All workmanship and welding shall be in accordance with the following:

> ABS "Rules for Building and Classing Steel Vessels Under 90 meters (295 feet) in Length" (for Hull)
>
> ABS "Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways," Part 3, Section 7, Passenger Vessels (for Superstructure)

Classification Society certification of the structure is not required, but structural calculations supporting compliance with one of the above listed Rules shall be submitted to the OWNER for approval in areas that the CONTRACTOR proposes any changes. Calculations shall show clear references to rules being used.

Construction details shall be in accordance with ABS' "Guide for Shipbuilding and Repair Quality Standards for Hull Structures During Construction," latest edition. Plating shall be fitted fair and free from buckles or uneven sight edges. All formed plates or shapes shall be formed true to the required alignment, shape or curvature. Where flanges are used for attachments, the faying edges shall be beveled and free from hollows. Shims shall not be used to correct improper fit. Members shall be in alignment before welding is undertaken. No fairing compounds shall be used. Warpage or distortion that prevents the installation of the final welded assembly into the boat is not acceptable.

"Panting" or "oil-canning" of any panel in shell, deckhouse or decks is not permitted. Filling compound shall not be used to compensate for unfairness in the boat structure. Every effort shall be exercised to construct a vessel with fair and undistorted surfaces. This shall include diligence for careful fit-up, proper weld sequences and utilizing minimum weldments to achieve required structural strength.

The maximum unfairness between hull, deck and house stiffeners shall be t/2, where "t" is the plate thickness.

Penetrations of deck, bulkhead and shell plating shall be reinforced as required to maintain structural integrity.

All cuts shall be neatly and accurately made with edges cleaned for welding. All sharp edges exposed to personnel or equipment shall be dressed or ground to avoid injury to operating or maintenance personnel or damage to equipment. Internal corners shall be filleted and external corners shall be rounded off. Ragged edges or sharp projections shall be removed.

All burning of notches and holes in the structure shall be carefully laid out and shall be regular in outline with jagged edges removed and with rounded corners. Semicircular "rat holes" shall be provided in framing members in way of passing welded seams or butts in the attached plating. Notches and rat holes shall be machine cut.

Where it is necessary to provide holes for passage of wiring, piping or ductwork through vessel structure, special penetration details shall be used to maintain structural and fire insulation integrity and oil/water/air tightness as appropriate. All penetrations of fire boundaries shall be collared and insulated on both sides of the fire boundary and as otherwise necessary to meet regulatory requirements. In general, penetrations through bulkheads shall utilize Nelson Firestop $4'' \times 6''$ transit or equal. All details of such penetrations shall be submitted to the OWNER for approval.

All edges or corners of the bulwarks which could have a fire hose dragged over or around them shall be radiused using 1 - 1/2 to 2 inch diameter pipe (or equivalent flanged radius).

The CONTRACTOR shall ensure that precautions are taken to prevent rusting of exposed plate and new welds. The OWNER is extremely concerned that excessive rust bloom will compromise the ability of the paint system to obtain a secure hold on the sub-surface, especially in way of the welds. Painting shall be conducted within a controlled environment, protected from the elements, through use of either permanent or portable structures. See SECTION 631 for a description of surface preparation and other coating requirements.

**Figure 1-14** Excerpts from written specifications (Courtesy of Jensen Maritime Consultants, Inc.)

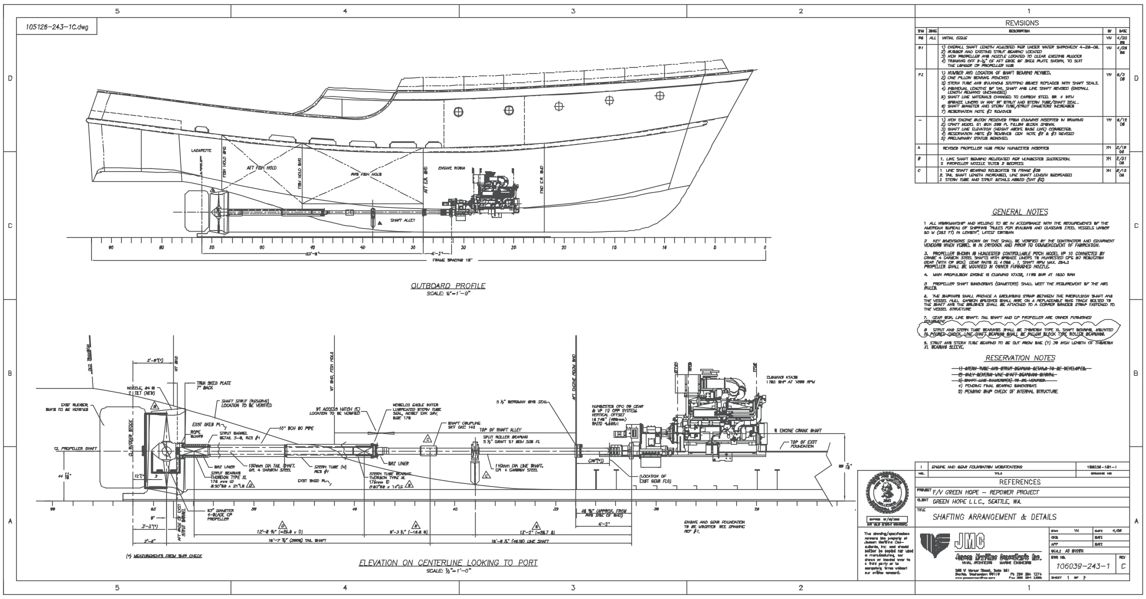
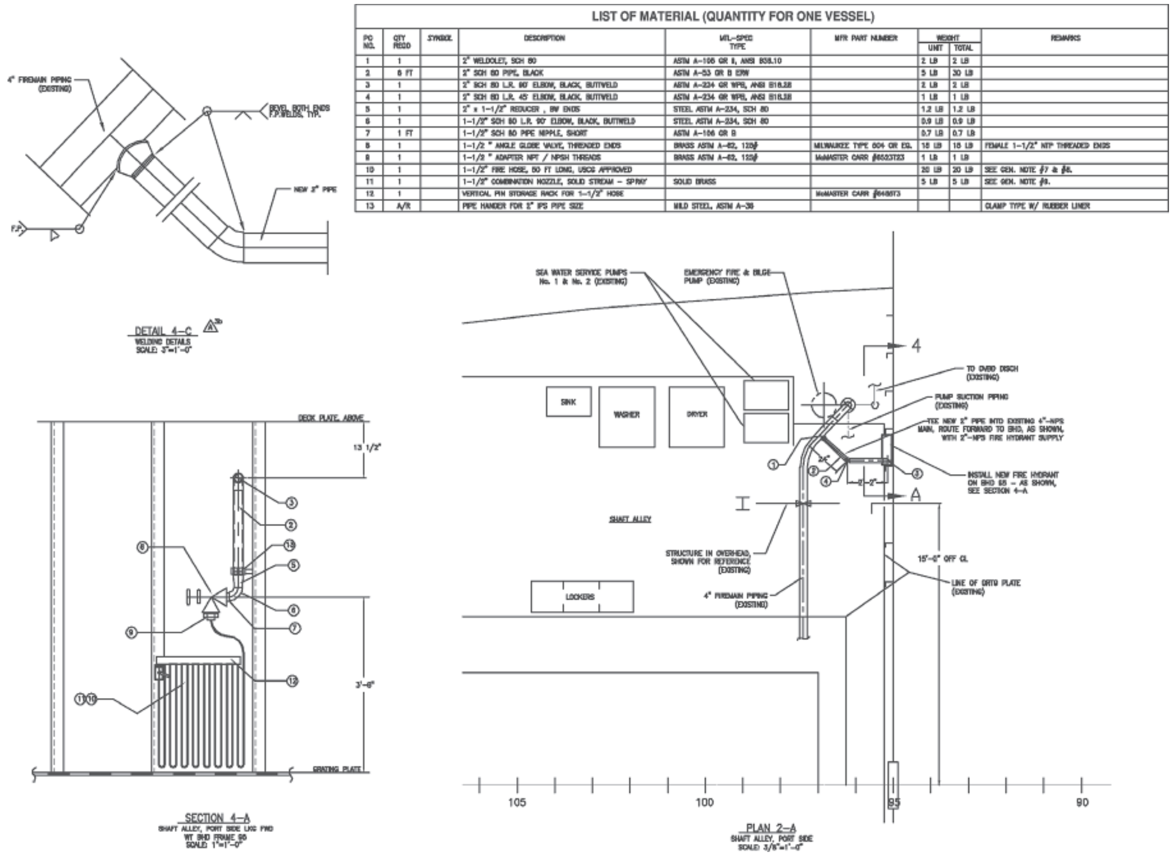



**Figure 1-15** Shaft assembly drawing (Courtesy of Jensen Maritime Consultants, Inc.)

or parts list. An assembly drawing with a bill of materials is shown in Figure 1-16.

Note that the term *specification* is also used in engineering design to refer to a target value, performance measure, or benchmark employed to evaluate the success of a design. Taken in this sense, specifications begin to emerge early in the design process, as the designer clarifies the client's or company's understanding of the problem, and the potential user's needs. Examples of performance specifications taken from the written tugboat specifications document cited in Figure 1-14 include:

- *Propulsion system shall consist of a pair of EPA Tier 1 certified, 4-cycle diesel engines with a minimum continuous rating of approximately 2480 BHP.*
- *The boat shall undergo a two-hour endurance trial run at the maximum engine rating. During this trial it shall be demonstrated that all mechanical parts of the propulsion unit and all auxiliaries are in satisfactory operating condition, and that propulsion system steady-state conditions are within engine manufacturer's tolerances. Inspections shall be carried out for leaks in all piping systems and any*




LIST OF MATERIAL (QUANTITY FOR ONE VESSEL)

| PC NO. | QTY REQD | SYMBOL | DESCRIPTION | MIL-SPEC TYPE | MFR PART NUMBER | WEIGHT UNIT | WEIGHT TOTAL | REMARKS |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | | 2" WELDOLET, SCH 80 | ASTM A-105 GR II, ANSI B36.10 | | 2 LB | 2 LB | |
| 2 | 6 FT | | 2" SCH 80 PIPE, BLACK | ASTM A-53 GR B ERW | | 5 LB | 30 LB | |
| 3 | 1 | | 2" SCH 80 L.R. 90° ELBOW, BLACK, BUTTWELD | ASTM A-234 GR WPB, ANSI B16.28 | | 2 LB | 2 LB | |
| 4 | 1 | | 2" SCH 80 L.R. 45° ELBOW, BLACK, BUTTWELD | ASTM A-234 GR WPB, ANSI B16.28 | | 1 LB | 1 LB | |
| 5 | 1 | | 2" x 1-1/2" REDUCER , BW ENDS | STEEL ASTM A-234, SCH 80 | | 1.2 LB | 1.2 LB | |
| 6 | 1 | | 1-1/2" SCH 80 L.R. 90° ELBOW, BLACK, BUTTWELD | STEEL ASTM A-234, SCH 80 | | 0.9 LB | 0.9 LB | |
| 7 | 1 FT | | 1-1/2" SCH 80 PIPE NIPPLE, SHORT | ASTM A-106 GR B | | 0.7 LB | 0.7 LB | |
| 8 | 1 | | 1-1/2 " ANGLE GLOBE VALVE, THREADED ENDS | BRASS ASTM A-62, 120# | MILWAUKEE TYPE 604 OR EQ. | 18 LB | 18 LB | FEMALE 1-1/2" NTP THREADED ENDS |
| 9 | 1 | | 1-1/2 " ADAPTER NPT / NPSH THREADS | BRASS ASTM A-62, 125# | McMASTER CARR #6523T23 | 1 LB | 1 LB | |
| 10 | 1 | | 1-1/2" FIRE HOSE, 50 FT LONG, USCG APPROVED | | | 20 LB | 20 LB | SEE GEN. NOTE #7 & #8. |
| 11 | 1 | | 1-1/2" COMBINATION NOZZLE, SOLID STREAM - SPRAY | SOLID BRASS | | 5 LB | 5 LB | SEE GEN. NOTE #8. |
| 12 | 1 | | VERTICAL PIN STORAGE RACK FOR 1-1/2" HOSE | | McMASTER CARR #6468T3 | | | |
| 13 | A/R | | PIPE HANGER FOR 2" IPS PIPE SIZE | MILD STEEL, ASTM A-36 | | | | CLAMP TYPE W/ RUBBER LINER |

**Figure 1-16** Assembly drawing with BOM (Courtesy of Jensen Maritime Consultants, Inc.)

*structural defects. The readings of all installed gauges and meters shall be recorded at 15-minute intervals.*

## COMMUNICATION

At this point, the product's development transitions from design to manufacture. The final step in the engineering design process is to communicate the design using written reports and oral presentations.

### Written Reports

Although they are better known for their math skills than for their verbal skills, most experienced engineers are in fact good writers. Written communication consumes a large portion of an engineer's work week. Written documents composed by engineers include letters, emails, memoranda, technical reports, technical papers, and proposals. The audience for these technical documents includes other engineers, designers, supervisors, vendors, regulatory agencies, and customers. Regardless of the audience and type of report, technical writing requires a clear, concise expression of what can be very complex issues, concepts, and arguments.

A typical outline for a technical report might include the following sections:

| | |
|---|---|
| Introduction | Discussion (of results) |
| Background | Conclusions |
| Procedure | References |
| Results | Appendices |

**Recommended report-writing steps**

When writing a technical report or paper, it is recommended that you break the writing process up into several distinct sessions. Try to start each session when you are at your best (e.g., early morning, late afternoon). Once the session begins, try to ensure that you won't be interrupted for at least a few hours. Finally, wait a day before starting the next session. Shown below is a series of session steps that can be used to write papers and technical reports.

1. *Brainstorm ideas*—In the first session, write down everything that you wish to say, making no effort to structure the material. The emphasis should be on the free flow of ideas. This session is probably best done using a pen and paper.
2. *Preliminary outline*—In the second session, attempt to structure the brainstorming output in bullet form. What are the topic headings and subheadings? How are the topics ordered? What material falls under which heading? At this stage, transition to a word processor, if you have not already done so.
3. *Detailed outline*—Read the initial outline, revising and amplifying as needed. Move things around, and add and delete material. Do the topic headings and bullet items easily transition and flow? Is there sufficient content to make the argument? If not, do more research to fill in the gaps. Amplify on the bullet items, adding detail as needed. Move from phrases to complete sentences.
4. *Start writing*—Normally with the introduction, but not necessarily. This is where the true struggle takes place. Progress can be painfully slow; concentration, determination, and grit are essential. Aim for coherence and continuity. After a significant struggle, you may have to settle for less. As long as an honest effort is made, a fresh start will almost always help. A good day's work is a couple of pages.
5. *Carefully and critically edit* what has already been written for coherence, continuity, grammar. Revise, rewrite, rearrange.
6. Critically reread the document from start to finish, making final editorial changes as necessary.

## Oral Presentations

As an engineer, you will occasionally be called upon to present the results of your work. Presentations are made to deliver progress and summary reports, to pitch an idea or proposal, and also to present a paper at a conference or technical society. Whatever the purpose, it is important to carefully prepare for, and then practice, the delivery of the presentation. When designing the presentation, it is important to know your audience so that you can anticipate and fulfill its needs. Good visual aids and graphics are important, as is a well-organized, logical development of the main ideas.

Some oral presentation guidelines include[13]:

1. Speak clearly so that you can be heard at the back of the room.
2. Vary your pitch or tone of voice occasionally.
3. Add enthusiasm to the delivery.
4. Expect to be somewhat nervous. Take a deep breath and relax a moment before beginning.
5. Start on time, stick to the schedule, and finish on time; do not go over.
6. Maintain eye contact with your audience. Pick a few individuals in the room and look at them as you present.
7. Use a pointer when appropriate.
8. Introduce all team members and the project title.
9. Show an overview slide describing the structure of the presentation.
10. Make your slides clear and crisp. Make sure all slides have sufficient contrast to show the text clearly.
11. Make bullets brief, typically with no more than five words.
12. Each bullet slide should require your explanation in order to be well understood by the

[13] Adapted from the Senior Project Design Manual used in GE 494, Senior Project Design, at the University of Illinois Urbana-Champaign.

audience. The audience will rely on you to bring the presentation together.

13. Photos should be large and clear. Use labels, arrows, etc. to define and point out important features.
14. When showing a graph, briefly define the axes and then tell the purpose of the graph and what it is intended to show.
15. Use PowerPoint® transitions sparingly.
16. Be prepared; know the purpose of each slide. Do not include any information on a slide that you cannot explain.
17. In developing your ideas, move from the general to the specific.
18. Distribute any handouts before the presentation begins.
19. Be clear about your conclusions and what they mean. Show how your conclusions and final recommendations satisfy the problem statement.
20. Have a *war chest* of extra slides for the Q&A period. Anticipate questions and prepare extra slides that will help you answer them.
21. In your practice sessions, notice how often you say "Um," "you know," and so on. Try to avoid this nervous habit. Silence is best when you have nothing to say.

## Beginning versus informed designer patterns

Beginning designers tend to approach design situations differently than more advanced, "informed" designers. The nine engineering design strategies and associated patterns in Table 1-5 contrast beginning versus informed design behaviors.

**Table 1-5 Beginning versus Informed Designer Patterns**[14]

| Engineering design strategy | Beginning designers | Informed designers |
|---|---|---|
| Understand the challenge: Problem solving vs. Problem framing | Do not grasp the basics of a design task, or treat it as a well-defined, straightforward problem that they prematurely try to solve | Understand basics of the design problem, and then delay making design decisions in order to explore, comprehend, and frame the problem better |
| Build knowledge: Skipping vs. Doing research | Skip doing research and instead build solutions immediately | Conduct investigations and research to learn about the problem, relevant cases, and how the system works |
| Generate ideas: Idea scarcity vs. Idea fluency | Work with just a few or just one idea, which they can get fixated or stuck on, and may not want to discard, add to, or revise | Practice idea fluency in order to work with lots of ideas by doing divergent thinking, brainstorming, etc. |
| Represent ideas: Surface vs. Deep drawing & modeling | Propose superficial idea that do not support deep inquiry of a system, and that would not work if built | Use multiple representation to explore and investigate design ideas and support deeper inquiry into how systems work |
| Weigh options and make decisions: Ignore vs. Balance benefits & tradeoffs | Make design decisions without weighing all options, or attend only to pros of favored ideas, and cons of lesser approaches | Use words and graphics to displace and weight both benefits and tradeoffs of all ideas before picking a design |

(*continued*)

[14]David P. Crismond and Robin S. Adams, The Informed Design Teaching & Learning Matrix, *Journal of Engineering Education, 101*, no. 4 (2012): 738.

**Table 1-5** Continued

| Engineering design strategy | Beginning designers | Informed designers |
|---|---|---|
| Conduct experiments: Confounded vs. Valid tests & experiments | Do few or no experiments on prototypes, or run confounded tests by changing multiple variables in a single test | Conduct valid experiments to learn about materials, key design variables, and the system work |
| Troubleshoot: Unfocused vs Diagnostic troubleshooting | Use an unfocused, nonanalytics way of viewing prototypes during testing and troubleshooting ideas | Focus attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them |
| Revise/Iterate: Haphazard or linear vs. Managed & iterative designing | Design in haphazard ways where little learning gets done, or do design steps once in linear order | Do design in a managed way, where ideas are improved iteratively via feedback. Strategies get used as many times as needed, in any order |
| Reflect on Process: Tacit vs. Reflective design thinking | Do tacit designing with little self-monitoring while working or reflecting on process | Practice reflective thinking by keeping tabs on design strategies and thinking |

(Modified from [14])

## CONCURRENT ENGINEERING

In the face of ever-increasing global competition, it has become necessary for successful manufacturing companies engaged in product development to continuously (1) shorten product development times, (2) improve product quality and performance, and (3) reduce product cost. A modern approach used to accomplish these daunting tasks is called concurrent engineering.

In the years after the Second World War, product development as conducted in large manufacturing companies was essentially a serial process, as shown in Figure 1-17*a*. The specialized functions of the company, represented as distinct departments, worked in comparative isolation. The free exchange of information across functional boundaries was not encouraged. The most commonly cited example of this behavior occurred at the interface between design and manufacturing, where the design group developed a design in isolation, and then *tossed it over the wall* to manufacturing. Manufacturing was then left to modify the design in order to meet manufacturing process, material, and equipment constraints. Although these changes were costly, a lack of competition made them bearable.

With the emergence, in recent decades, of a formidable global competitiveness, these inefficiencies can no longer be tolerated. ***Concurrent engineering*** is a team approach to product design in which team members, representing critical business functions, work together under the coordination of a senior manager. The cross-functional team is typically composed of members from such areas as sales/marketing, industrial design, design engineering, industrial engineering, manufacturing engineering, purchasing, and production. See Figures 1-17*a* and *b* for a graphical comparison of the concurrent and traditional engineering models.

One of the benefits of concurrent engineering's team approach is the open exchange of product information. Concurrent engineering is sometimes represented in association with the single most important source of product information, the CAD database, as shown in Figure 1-18.

Although concurrent engineering strives to incorporate all aspects of a product's life cycle (i.e., design, manufacture, distribution, service, and disposal) into the product's development, the central motivation for concurrent engineering is to ensure that manufacturing considerations are taken into account early and throughout

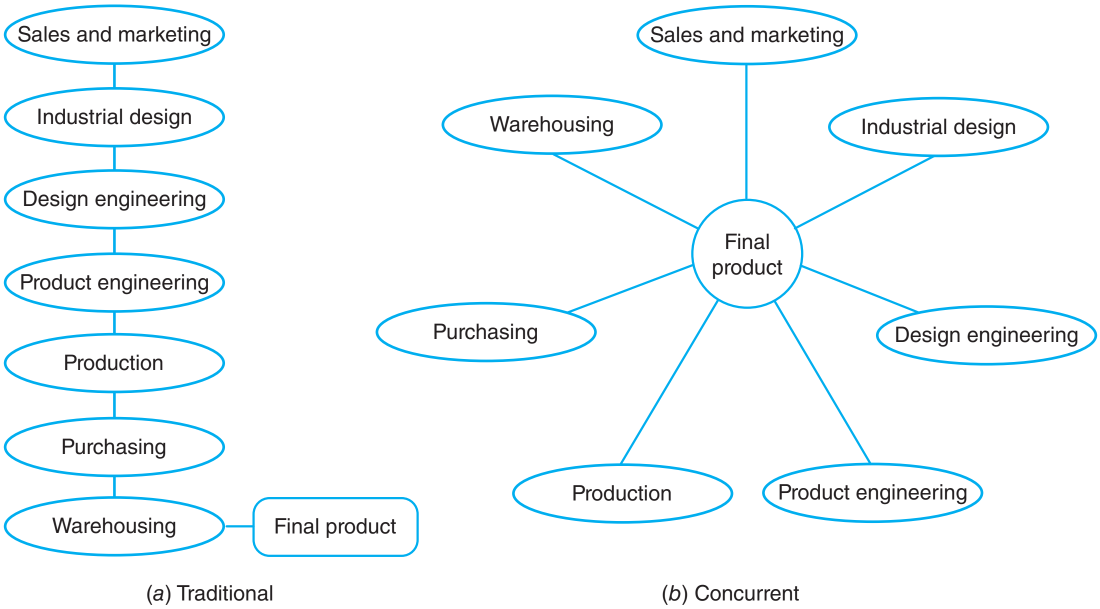



**Figure 1-17** Traditional versus concurrent engineering

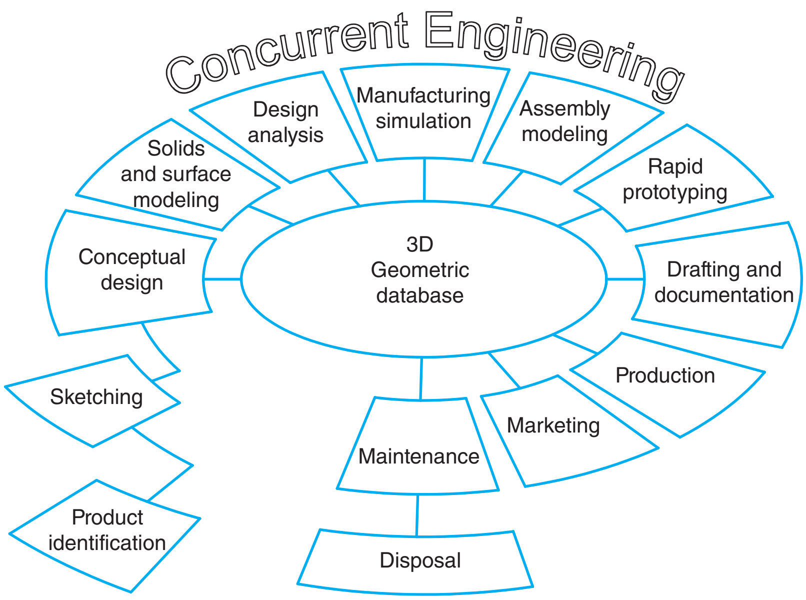



**Figure 1-18** Concurrent engineering and the CAD database (Courtesy of Barr, Kreuger, and Juricic)

the entire course of the design process. In the following section, on design for manufacture and assembly, this point is addressed more fully. The chapter then concludes with a discussion of another one of concurrent engineering's most important attributes, teamwork.

## Design for Manufacture and Assembly

Design changes occurring late in the design process are especially detrimental to a product's cost, quality, and time to market. Design for Manufacture (DFM) and its cousin Design for

Assembly (DFA) are relatively new areas that strive to minimize these late-occurring design changes by formalizing the relationship between design and manufacture. Whereas Design for Manufacture aims to improve the fabrication of individual parts, Design for Assembly strives to reduce the time and cost required to assemble a product. Taken together, DFM and DFA practices help ensure that the product and the manufacturing processes used to produce it are designed together. Recently a new term, Design for X (DFX), has become popular. DFX describes any of the various design methods that focus on specific product development concerns. These include Design for the Environment, Design for Reliability, Design for Safety, Design for Quality, and so on.

Here are some of the more important DFMA guidelines:

- ***Minimize the total number of parts***—The fewer the number of parts, the easier and faster the product's assembly.
- ***Minimize part variations***—This can be accomplished, for example, by using fasteners of the same size throughout.
- ***Design parts to be multifunctional***—A single part can be designed to serve more than one purpose, eliminating the need for additional parts.
- ***Design parts for multiuse***—Use the same part in different products.
- ***Design parts for ease of fabrication***—Near-netshape manufacturing processes (e.g., injection molding) are best; avoid machining if possible.
- ***Design parts with self-fastening features***—Use snap and press-fits whenever possible; avoid screws, bolts, and so on.
- ***Use modular design***—Design self-contained elements, blocks, or chunks that can be fabricated under ideal conditions and then connected to the main assembly.
- ***Minimize assembly direction***—Design products to be assembled along a single, preferably vertical axis (this is also called z-axis loading).
- ***Minimize handling requirements during assembly***—Positioning parts is costly; design features can be used to simplify positioning; avoid parts that tangle.
- ***Maximize compliance in assembly***—Use generous tapers, chamfers, radii; guiding features; use one component as a base.

## TEAMWORK

As we have seen, the adoption of concurrent engineering is credited with enhancing productivity in design and manufacture, enabling companies engaged in product development to maintain and even increase market share, despite the recent upsurge in global competition. Teamwork, as a result, is the single most important distinguishing factor of the concurrent engineering philosophy. Teams are increasingly common on projects and in engineering firms. And even apart from this recent trend, engineering design has always been a social activity relying on teamwork skills like communication, collaboration, and cooperation.

A ***team*** is a group of people with complementary skills and knowledge who work together toward common goals and hold one another mutually accountable. ***Teamwork*** consists of a demonstrated collaborative attitude and the ability to accomplish team goals.

There is of course no assurance that a team will outperform a collection of individuals. Research suggests that there are four identifiable levels of team performance. These include teams that: (1) perform below the level of the average member, (2) don't quite get going but struggle along at, or slightly above, the level of the average member, (3) perform quite well, and (4) perform at an extraordinary level, where the members are deeply committed to one another's personal growth and success.[15] Research also suggests that sufficient time is necessary for a team to reach the higher performance levels.[16]

Successful teams are characterized by certain traits or skills. These include the use of group

[15] Smith, 2000.

[16] Eggert, 2005.

**Table 1-6 Code of Cooperation, Boeing Airplane group, training manual for team members**

**Every member is responsible for the team's progress and success.**

1. Attend all meetings and be on time.
2. Come prepared.
3. Carry out assignments on schedule.
4. Listen and show respect for the contributions of other members; be an active listener.
5. Constructively criticize ideas, not persons.
6. Resolve conflicts constructively.
7. Pay attention; avoid disruptive behavior.
8. Avoid disruptive side conversations.
9. Only one person speaks at a time.
10. Everyone participates; no one dominates.
11. Be succinct; avoid long anecdotes and examples.
12. No rank in the room.
13. Respect those not present.
14. Ask questions when you do not understand.
15. Attend to your personal comfort needs at any time, but minimize team disruption.
16. Have fun.

norms, as well as communication, leadership, decision making, and conflict management. ***Group norms*** are guidelines or standards of behavior that are agreed upon by the group. By establishing and adhering to these guidelines, groups can avoid many disruptive conflicts. Table 1-6[17] shows an example of group norms.

Group decision making is considerably more difficult than a decision taken individually. There are a number of ways to make a group decision, ranging from decision by authority to consensus. A decision based on authority takes the least amount of time, whereas decisions based on consensus require more time but generally result in the best decision. A consensus decision is one in which the team thoughtfully examines all the issues and agrees upon a course of action that does not compromise the strong convictions of any team member.

Conflicts inevitably arise between team members. A conflict is a situation in which the action of one person interferes with the actions of another person. Conflicts can be either constructive or destructive. In a constructive conflict, the source of the disagreement is based on ideas or values, whereas in a destructive conflict, the dispute is based on personality. In order to function properly, it is essential for teams to develop rules that prohibit destructive conflict.

There are a number of strategies for dealing with conflict. These include:

1. ***Avoidance***—simply ignore the situation, and hope that the problem resolves itself over time.
2. ***Smoothing***—let the other side have his or her way.
3. ***Forcing***—one side imposes a solution.
4. ***Compromise***—meet the other side halfway. Though sometimes successful, this approach does not get to the underlying cause of the disagreement.
5. ***Constructive engagement***—the two parties strive to get to the heart of the matter and then work to resolve the situation through negotiation. Only this approach offers the possibility of reaching a satisfactory resolution to a serious conflict.

[17]Taken from Smith, 2000.

## QUESTIONS

### TRUE OR FALSE

1. Engineering design involves both analysis and synthesis.
2. A component can be either a part or a subassembly.
3. Design criteria serve to establish maximum, minimum, or permissible ranges for physical or operational properties of a design.
4. Design for Manufacture and Assembly (DFMA) guidelines include the minimization of the number of parts in a product.

### MULTIPLE CHOICE

5. Which of the following is not a stage of the product development process?
   a. Sales/marketing
   b. Industrial design
   c. Engineering design
   d. Product design
   e. Manufacturing

SS 6. A good problem statement includes:
   a. An undesired initial state
   b. A desired goal state
   c. Obstacles that prevent going from the undesired to the desired state
   d. All of the above

7. Design __________ are used to qualitatively judge alternative design solutions.
   a. Specifications
   b. Criteria
   c. Constraints
   d. Phases

8. Informed designers often differ from beginning designers in that *informed designers*: SS
   a. Treat a design task as a well-defined, straightforward problem
   b. Use gestures, words, and artifacts to explore and communicate their design plans
   c. Make drawings, construct physical prototypes, and create virtual models that help them develop deeper understandings of how their designs function
   d. Propose and sketch ideas that superficially resemble viable solutions
   e. All of the above
   f. a and b
   g. b and c
   h. c and d