1

INTRODUCTION TO ENGINEERING DECISION MAKING

Learning Objectives:

After studying this chapter, the reader will be able to do the following:

1. Identify and describe two types of decisions that engineers make (Section 1.2).
2. Classify the decisions that engineers make (Section 1.2).
3. Describe how optimization is related to decision making (Section 1.3).
4. Describe how problem solving is related to decision making (Section 1.4).
5. Explain why decision making is part of risk management (Section 1.5).
6. Identify problems that can occur in decision making (Section 1.6).
7. Identify the benefits of improving decision making (Section 1.7).
8. Describe a decision from three perspectives (Section 1.8).

1.1 INTRODUCTION

Why should engineers study decision making? What is engineering decision making?

People have always made decisions, but analyzing decision-making processes and developing better decision-making methods are more recent activities. Our ability to

Engineering Decision Making and Risk Management, First Edition. Jeffrey W. Herrmann.

analyze decisions has increased as mathematics, especially the theory of probability, has developed. In the 1700s, Daniel Bernoulli analyzed risky decisions and described how the relative values of alternatives depend on the preferences of the decision maker (Bernoulli, 1954). Ramsey (1964) developed a theory for decision making based on probability theory and utility. von Neumann and Morgenstern (1944) formalized the theory of expected utility and the analysis of multiplayer games, which is now known as game theory. Early works on game theory include Borel (1921), von Neumann (1928, 1959), and Hotelling (1929), who analyzed a game related to product differentiation. The works of Savage (1954), Raiffa (1968), Schlaifer (1969), Benjamin and Cornell (1970), and Keeney and Raiffa (1976) have been cited as influential early textbooks. Buchanan and O'Connell (2006) surveyed the history of decision making and the roles of intuition, risk, groups, and computing in decision making.

Now, what about engineering decision making? Scientists use their observations of natural phenomena to generate scientific knowledge, but engineers use their knowledge of the world to design products and systems that can perform needed functions while satisfying certain requirements.

To design a product or a system or to plan an activity, an engineer must make decisions. The engineer decides that a component will use a certain material, will have a certain shape, and will be made in a certain way. The engineer decides how the activity will be performed, who will do which tasks, and when they will be done. There are many possible choices, and the engineer must select one. This is the essence of decision making.

The process of making a decision, similar to cooking, transforms inputs into outputs. Cooking transforms ingredients such as pasta, ground beef, tomato sauce, spices, mozzarella, ricotta, and parmesan cheese into an appetizing dish such as lasagna. Decision making transforms information. The input information includes knowledge about physical phenomena, manufacturing processes, costs, customer requirements, regulations, and existing designs. Of course, there may be uncertainties about this information. The output is new information: a description of a design or a plan. That is, engineering decision making transforms existing information into new information.

Those engineers who improve their ability to make decisions should generate designs and plans that are more effective and more efficient. This will help the engineers and their organizations to be more productive, more successful, and more valuable. Because engineers are trained in mathematics, statistics, analysis, and modeling, they have the prerequisites to study and understand the techniques necessary to improve decision making. Because engineers have experience in designing, testing, and building objects and systems, they have the skills to apply these decision-making techniques to real-world problems.

Some of the techniques covered in this text can help a decision maker find the "best" alternative (the "right answer"). Studying decision making, however, should produce not only better answers but also new ways of thinking about decisions. Thinking more carefully about a decision will lead to better understanding even if no formal technique is applied. It can help one to choose an appropriate process and avoid decision-making errors. It can encourage one to consider how much information is really needed. It can lead one to see the potential problems with the available alternatives and find ways to reduce those risks.

Thinking about the merits of the alternatives, the criteria used to evaluate them, and the uncertainties involved can help engineers articulate and record the rationale for their decisions, which can help them justify their decisions to their peers and superiors and avoid errors during future redesigns. Recording design rationale can also support collaboration, design reuse, and training other engineers (Lee, 1997).

This text discusses three perspectives on decision making: (1) the problem-solving perspective, (2) the decision-making process perspective, and (3) the decision-making system perspective. These are discussed in detail in Section 1.8. The material included herein will cover important topics on decision making, present tools for helping engineers make better decisions, and provide examples to illustrate the concepts and techniques. The author hopes that students and engineers who study this material and apply these concepts and techniques will become better decision makers.

Studies of how decision makers make choices in practice have revealed that some decisions are made using simple heuristics (Gigerenzer *et al.*, 1999), and others are made without considering multiple alternatives (cf. Klein *et al*., 2010). Improving decision making can go beyond the valuable insights that are gained by understanding these phenomena, however. The mathematical models used in the study of decision making are, like all models, approximations of what really happens. Still, they can be valuable if they are useful to those who need to make decisions. The text, therefore, includes a variety of models that have been generally useful.

In particular, this text describes multiattribute utility theory (MAUT), the analytic hierarchy process (AHP), models for representing risk preferences, and game theory models. As Luce and Raiffa (1957) noted, such models do not describe what all decision makers do, and they do not describe what decision makers should do in an absolute sense (in all cases). They do, however, attempt to say which alternative is the best way to achieve the decision maker's particular goals.

This section began with two questions and provided some answers. These answers, however, lead to additional questions that this text will address:

- What is the value of improving decision making?
- Which alternative is the best one?
- How should our group make a decision?
- How can one compare alternatives in the presence of uncertainty?
- How can we decide when we do not know what the other guy is going to do?
- Which decision-making process is the most appropriate?
- Should we gather more information before deciding?
- How can we reduce risk?
- How do organizations make decisions?
- How can we improve decision making in our organization?

1.2 DECISION MAKING IN ENGINEERING PRACTICE

In practice, engineers make many different types of decisions as they design products and systems. In general, the decisions that engineers make can be classified into two broad categories:

1. *What should the design be?* Design decisions determine the overall structure, shape, size, material, manufacturing process, and components of an object or a system. These generate information about the design itself and the requirements that it must satisfy. Design decisions may involve manufacturing processes and systems. Deciding that gear hobbing will be used to make the bull gear for a rear differential is a design decision, and deciding where to place the equipment (including the horizontal hobbing machines) in a machine shop is a design decision, but deciding which machinist should operate the hobbing machine and which gears should be machined tomorrow is not, however (it is a production management decision).
2. *What should be done?* Management decisions control the progress of a design process or other activity. They affect the resources, time, and technologies available to perform activities. They define which activities should happen, their sequence, and who should perform them. That is, they determine what will be done, when it will be done, and who will do it. Project management includes many decisions, such as planning, scheduling, task assignment, and purchasing.

Example 1.1 Kidder (1981) described the development of a minicomputer (the Eclipse MV/8000) by a team of engineers at Data General. Although the technology described is now obsolete, the book depicted many of the decisions that the engineers made during the computer's development. Management decisions and design decisions occurred at different levels in the organizational structure. Decisions by those who had more authority and responsibility affected more people, more of the process, and more of the product. The following actions were some of the management decisions (the names West, Wallach, Rasala, etc., refer to people on the development team):

- The vice president of engineering approved the project.
- West decided to hire inexperienced engineers who had just graduated.
- West decided to have two teams: one for designing the hardware and the other one for designing the microcode.
- West decided that Wallach should be the architect.
- Wallach decided to begin designing the architecture by organizing the memory.
- West reviewed the designs.

- Rasala created the debugging schedule.
- West approved using microdiagnostic programs.
- West approved building a simulator for testing microcode.
- Alsing picked Dave Peck and Meal Firth to write simulators.
- West decided who would work on which new projects.
- Rasala decided to work in the lab to increase morale.

The following actions are some of the design decisions:

- West decided that the new computer should be a 32-bit computer that can run older programs written for another computer.
- Wallach decided to worry about preventing accidental damage, not malicious theft.
- Wallach decided that the memory protection scheme should use the segment number as the security level.
- Wallach defined the instruction set.
- Engineers negotiated the design details.
- West decided that the computer would use PAL integrated circuits.
- The engineers wrote the microcode and the schematics.
- Holland organized the microcode.
- West and Rasala decided to keep the arithmetic logic unit on one board by limiting its functionality.
- West decided which cables and connectors the computer should use.
- West decided how the machine should be started.

1.3 DECISION MAKING AND OPTIMIZATION

Decision making involves generating and evaluating alternatives and selecting the most preferred one that satisfies given requirements. Optimization involves finding the best solution from a set of feasible solutions (cf. Kirsch, 1981; Papalambros and Wilde, 2000; Arora, 2004; Ravindran *et al*., 2006). From a certain level of abstraction, therefore, decision making resembles optimization.

Certainly, in some cases, the decision-making process is to formulate and solve an optimization problem. Such cases are characterized by a relatively large amount of useful knowledge about the situation and a clear consensus on the objective function. For example, automotive firms have used optimization to find the best structural design of an automobile frame in order to make it as strong and light as possible (see Detwiler *et al.*, 1996, for an early example at General Motors) and have developed multidisciplinary optimization approaches to find the most profitable vehicle design during the early design phase (Fenyes *et al*., 2002).

When the optimization requires using analysis software (like finite element analysis) to evaluate designs, the computational effort of solving the optimization problem may be the primary challenge. The study of optimization is usually considered as a topic of interest in applied mathematics and operations research and engineering design.

Viewing decision making as optimization can be inappropriate, however, in situations when there is insufficient information to formulate an optimization problem or there is no consensus on the objective function. This will be discussed in more detail in Chapter 7.

1.4 DECISION MAKING AND PROBLEM SOLVING

Although the concept of decision making (the process of selecting an alternative) is generally clear, the idea of problem solving is less straightforward. For our purposes, it will be important to note two different types of problems.

The first type of problem is a predefined, clearly stated question that must be answered through calculation or search. There is usually a "right" answer that can be judged strictly objectively. Word problems in mathematics, operations research, physics, and engineering science textbooks are generally this type of problem (e.g., "Given this set of ten jobs that need processing on a set of ten machines, which schedule minimizes the total time needed to complete all of the jobs?"). Navigation systems and online map Web sites solve this type of problem when they provide directions for the fastest route from a starting point to a destination. Thus, some of these problems are optimization problems, which were discussed in Section 1.3. This type of problem may involve predicting how the state of a natural or a man-made system will change over time or determining unknown aspects of the system state from those that are given (Hazelrigg, 1996).

The second type of problem is an "issue," an undesirable situation that a person or an organization wishes to change. Solving this type of problem can be a messy process. When a piece of manufacturing equipment stops working unexpectedly, an issue has appeared, and the factory has a problem to be solved. To solve this problem, the firm has to investigate the cause of the problem and do something to get the equipment working again.

For this type of problem, Powell and Baker (2004) defined the following six-stage problem-solving process:

1. Explore the mess: search for problems and opportunities, accept a challenge, and start systematic efforts to respond.
2. Search for information: gather data and impressions, observe the situation from many different viewpoints, and identify the most important information.
3. Identify a problem: generate different potential problem statements and choose a working problem statement.
4. Search for solutions: develop different alternatives and select one idea (or a few ideas) that seem most promising.

5. Evaluate solutions: formulate criteria for reviewing and evaluating ideas and select the most important criteria, then evaluate and revise the idea(s), and then select a solution.
6. Implement a solution: identify implementation steps and required resources and then implement the solution.

Other discussions of problem solving consider very similar steps. This description shows that decision making is a component of the problem-solving process. The general decision is something like "What should we do to solve this problem?" Decisions occur in many contexts besides solving problems, however, so it is clear that decision making is not the same as problem solving.

Steps 3–5 of the above problem-solving process explicitly mention decisions: choosing a working statement (in Step 3), selecting the most promising ideas (in Step 4), selecting the most important criteria (in Step 5), and selecting a solution (in Step 5). Each is an interesting decision, and together, they are a part of how an organization decides what to do. The concept of how making a decision requires making many decisions will be considered further in Chapter 7.

1.5 DECISION MAKING AND RISK MANAGEMENT

In general, the term "risk" denotes uncertainty about what will happen in the future. Risk management is the process of identifying risks, assessing them, and selecting and implementing risk mitigation activities.

Problem solving handles issues, but risk management considers potential problems (cf. Kepner and Tregoe, 1965), how to prevent them from happening, and how to minimize their impact. A manufacturing firm concerned about the possibility of missing customer due dates will consider, among other things, the likelihood that a crucial machine will fail and what can be done to prevent its failure (by performing more preventive maintenance) and minimize the time required to repair it if it should fail (by investing in some spare parts, for instance).

Contingency plans are useful for risk mitigation, but problems can occur when they are activated, so one has to consider those potential problems and mitigate those risks as well. For example, installing a spare part is a reasonable contingency plan if the machine fails; however, a potential problem is that the spare part may be unavailable if it is lost or damaged before it is needed. Thus, mitigating that risk becomes necessary.

Formal processes of risk management (discussed in Chapter 9) include a decision-making step: which risk mitigation activity (or activities) should the organization perform? Ideally, organizations would implement many risk mitigation activities. Unfortunately, time, money, and other resources make this impossible, so firms have to choose. Important aspects of risk management are also covered in Chapter 2 (risk acceptance criteria), Chapter 5 (decision making under uncertainty), Chapter 6 (game theory), Chapter 7 (the decision-making cycle and analytic-deliberative decision making), and Chapter 8 (the value of information).

1.6 PROBLEMS IN DECISION MAKING

Debacles such as the Ford–Firestone feud and the design of the Denver International Airport are "decisions with bad practice producing big losses that become public" (Nutt, 2003). Engineers should avoid debacles. As might be expected, not all poor decisions lead to debacles; they lead instead to wasted time, unnecessary costs, lost opportunities, a poor reputation, damaged relations, and other undesirable outcomes.

Decision makers make poor decisions for many reasons. The causes range from the actions and characteristics of individual persons to the policies and culture of organizations. Decision makers can select the wrong process or mismanage the process; generate too few alternatives, too many alternatives, or useless alternatives; select inappropriate or irrelevant objectives; evaluate alternatives using outdated or incomplete or incorrect information; select inferior alternatives; implement the chosen alternative poorly; and fail to learn from these types of mistakes. Section 9.8 reviews specific problems and discusses how to reduce the risk of a bad decision.

1.7 THE VALUE OF IMPROVING DECISION MAKING

Improving decision making (through the use of structured decision analysis, for instance) not only helps decision makers select better alternatives but also gives them more insight into the decision situation. The first step is to think about how one makes decisions. Stepping back to reflect on the process to be followed can generate insights into the opportunities to improve the decision-making process. The possible improvements include more relevant objectives, better alternatives, more appropriate measures for evaluating the alternatives, and more logical techniques for combining these values into a measure that better reflects the decision-maker's values and preferences. Better decision-making techniques can save time by focusing time and attention on constructive activities. Standard decision-making processes can increase consistency and transparency and facilitate further improvement.

Consider Rose, a decision maker, who wants to improve her decision making with some type of tool or some other change in the decision-making process (which we will call the "improvement"). In theory, for a particular decision, Rose could calculate the difference between the expected value of the alternative that she would choose if she uses the improvement and the expected value of the alternative that she would choose if she does not use it.

By evaluating the difference between the best alternative (which was chosen) and the other alternatives, a review of 37 projects at Eastman Kodak estimated that using decision analysis added between \$5.24 and \$10.02 million per project (Clemen and Kwit, 2001). Gensch (2001) estimated that a manufacturer of heating and cooling systems more than doubled the profitability of its new products after implementing a new decision process that required gathering better information about the alternatives and used a mathematical model for evaluating them. Parnell and Bresnick (2013) reported that Chevron executives have estimated that using decision analysis was worth billions of dollars every year and that the benefits dwarf the small marginal cost of doing decision analysis.

In addition to the economic benefits, decision analysis has improved decision making by improving communication among those making the decision, identifying risk factors earlier, and planning contingencies (Clemen and Kwit, 2001).

1.8 PERSPECTIVES ON DECISION MAKING

Aristotle introduced the concept of four causes to provide a way to explain reality, and other philosophers, notably Thomas Aquinas, adopted this approach as well. In this approach, an object has four causes (Feser, 2009):

- a *final cause* that is the object's purpose or goal or end;
- a *formal cause* that describes its form or shape;
- a *material cause* that describes the material from which it is made; and
- an *efficient cause* that explains what made it or how it was made.

The traditional design concerns (function, form, material, and manufacture) correspond exactly to these four causes. These causes can be viewed as answering three questions: Why? What? and How? In the same way, to understand a decision, it is useful to consider the following questions about it: *Why is the decision being made? What is the decision? How is the decision made?*

The answer to "Why?" describes the relation among the objectives considered when making the decision, the decision-maker's other objectives, the location of this decision within the organization's decision-making system, and the roles of others in the organization. This is the *decision-making system perspective*.

The answer to "What?" describes the set of alternatives being considered, the constraints that the alternatives had to satisfy, and the objectives used to evaluate and rank the alternatives. This is the *problem-solving perspective*.

The answer to "How?" describes the process of generating alternatives, collecting information about the alternatives, and evaluating the alternatives. This is the *decision-making process perspective*.

The introduction to this chapter mentioned that decision making is a process similar to cooking. Let us extend that metaphor as follows. Picture a busy restaurant kitchen in which numerous chefs and other employees use various tools and appliances at different workstations to prepare and cook different types of food. The ingredients move around the kitchen and are used to make individual items (such as entrees and sides), and these items are used to prepare complete plates that are delivered to the customers. If we look at one particular plate of food, we can consider its contents, which answers the question "What?" If we look at the steps needed to make the food on the plate, we can understand the process used to transform a set of ingredients into dinner, and this answers the question "How?" Finally, if we look at the entire kitchen, we see a system of people who are processing food and creating dinners for customers, and this answers the question "Why?" In this image, each plate that is completed corresponds to a decision that is made; the different workstations in the kitchen correspond to the steps in the decision-making process; and the chefs and their staff are the organization (the decision-making system).

Example 1.2 Consider Boeing's decision to move its corporate headquarters to Chicago ("Inside Boeing's Big Move," 2001). *Why did Boeing make that decision*? Boeing wanted a new location for its corporate headquarters as part of its strategy to develop a headquarters that was distinct from its existing businesses and to focus on growth opportunities around the world. This decision followed other decisions about the company's strategic growth plans and led to many decisions about how to implement the move. *What was the decision*? Boeing chose an office building for the location of its headquarters. The building had to be near a major airport in the United States, and the company wanted to minimize travel time throughout the country and internationally and to be near politicians and financial firms. *How was the decision made*? The senior vice president of Boeing and other executives first picked a short list of three cities. Real estate professionals provided information about available buildings. Then, the senior vice president, with a team of colleagues, visited and evaluated multiple sites in those cities. Finally, he presented the information to Boeing's chief executive officer, who selected a site in Chicago.

Each of these three questions reflects a different perspective on the decision. The organization of this text is structured around these three perspectives. The text will first consider the components and structure of decisions (Chapters 2–6), which is the problem-solving perspective. Then, the text will discuss the decision-making process perspective: how people make decisions through decision making and risk management processes (Chapters 7–9). Finally, the text will describe decisions from the decision-making system perspective by considering the decision-making behaviors and information flow within organizations and how to improve those decision-making systems (Chapters 10 and 11).

EXERCISES

1.1. What are the two types of decisions that engineers make?

1.2. Give two examples of each type of decision.

1.3. Walton (1997) described the process that a team of Ford engineers used to develop the Taurus. Classify each of the following decisions as a design decision or a management decision:

- **(a)** Selecting a place for the development team to work.
- **(b)** Selecting the shape of the headlamps.

(c) Selecting which sketch to use for a clay model.
(d) Deciding to use a longer wheelbase.
(e) Agreeing to fund tooling and plant renovation.
(f) Deciding to have another market research clinic with current Taurus owners.
(g) Deciding to spend $200,000 to make a clay model of a competitor's car for the market research clinic.
(h) Approving $700 million in additional investment.
(i) Selecting inset doors instead of hard-top doors or limousine-style doors.
(j) Deciding to manufacture a one-piece bodyside.
(k) Deciding that the door sills will be black.

1.4. Why is optimization relevant to decision making?

1.5. What is the role of decision making in risk management?

1.6. List two problems that can occur in decision making.

1.7. List two benefits that can result from improving decision making.

1.8. What are the three perspectives for understanding a decision?

1.9. Consider a decision that you have made recently. Describe it from all three perspectives.

1.10. During the development of the Apollo spacecraft, NASA engineers (who were unsure about the actual conditions on the moon) decided that the landing gear design should be appropriate for surfaces like those found in Arizona (Nelson and Men, 2009). Is this a design decision or a management decision?

1.11. Ben Moreell was a civil engineer who later became an admiral in the U.S. Navy. Consider Moreell's decision to recruit skilled constructions workers for the Navy's Construction Battalions (the Seabees) in World War II (Kennedy, 2013). Was this a design decision or a management decision?

1.12. Consider Boeing's selection of a new corporate headquarters in 2001 (cf. "Inside Boeing's Big Move"). For each of the following aspects of this decision, note if it is most relevant to (1) the problem-solving perspective, (2) the decision-making process perspective, or (3) the decision-making system perspective:
(a) The availability of educated workforce and presence of other major business headquarters.
(b) Office buildings that would be available in September of that year.
(c) The roles of the board of directors, the strategy council, and the senior vice president.
(d) Flying around in a helicopter to look at potential sites.

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