Chapter 3

Tools for Analysis and Synthesis

This chapter introduces two types of tools used to aid communication, analysis, and synthesis. Section 3.1 introduces various types of models and section 3.2 discusses charts of various kinds. In both sections, the focus is on the tools rather than the examples.

3.1 USING MODELS FOR SAFETY ANALYSES

Models are representations of systems. This section introduces the idea of modeling systems and provides examples of some types of models useful for safety analyses. The types of models introduced here are physical models, graphic relationship models, physics models, and mathematical models.

3.1.1 Physical Models

Physical models are three-dimensional physical constructions made similar to the actual system. For example, a model train is a scaled-down version of a real train. Flight simulators are made to provide a safe environment for pilot training and skill enhancement. Driver simulators are used for highway safety research. Mock-ups are commonly made during product design, and sculptors often make small models before starting their full-scale work. Physical models are also used for usability testing of products and assembly workstations.

3.1.2 Graphic Relationship Models

System safety projects start with a description of the system that includes a conceptual representation of the system. *Graphic relationship models* are practical for modeling a specific system or a generic system.

Risk-Reduction Methods for Occupational Safety and Health, First Edition. Roger C. Jensen.

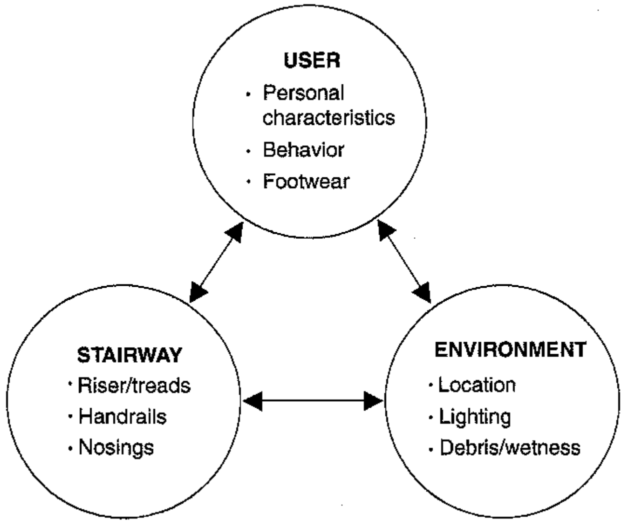

Figure 3.1 Example of graphic relationship model for user–stairway–environment system. Adapted with permission from Ref. 1.

The example of a graphic model representing a generic system comes from a study by Cohen et al. (Figure 3.1).[1] They reported findings from in-depth investigations of 80 stairway falls. Their information about the cases is organized into a graphic model depicting the interactive nature of three system elements: user, stairway, and environment. The graphic model is an effective way to show that a change in one element may, and often does, affect one or both the other elements.

3.1.3 Physics Models

Models based on the laws of physics are called, in this book, *physics models*. They typically consist of a diagram paired with one or more equations. Readers may review their college physics textbook to see numerous examples. In one popular physics textbook, the authors provide a general problem-solving strategy in which a diagram is the second of eight steps: read problem, draw diagram, label physical quantities, identify principles, choose equations, solve equations, substitute known values, and check answer.[2] Thus, even physics textbook authors recognize the utility of developing a diagram before choosing equations.

Electrical circuit diagrams are one type of physics model. These display components of a circuit arranged as the actual circuit. The equations for describing current, voltage, and resistance are the same for the actual circuit as for the diagram. Some people call such models analog models because the diagrams are analogous to the actual circuit.

Another kind of physics model uses a free-body diagram as the analog for actual objects and forces. These diagrams depict a solid object (free body) with vectors

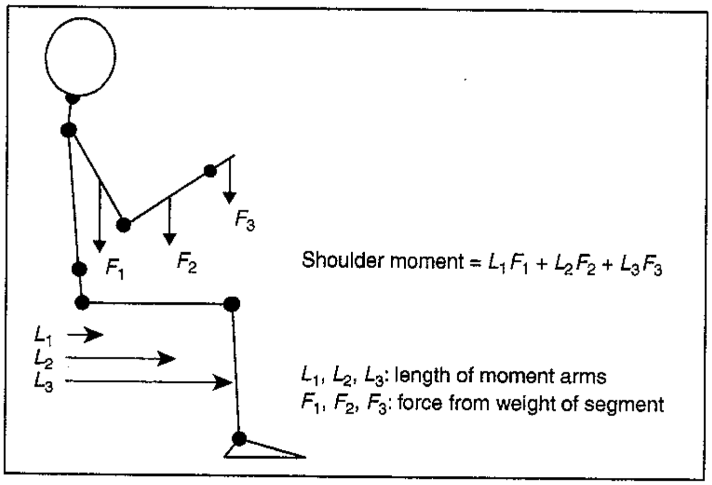

Figure 3.2 Example of force diagram for a biomechanical model.

indicating forces, directions, and lines of action. The equations paired with the diagram indicate how the attributes of the vectors relate. For example, suppose the system of concern is an industrial workstation in which a seated person works with arms forward in a fixed position. Because the position is held fixed, the whole body is treated as a free body. The diagram in Figure 3.2 may be used to show gravitational forces acting on the upper arm, forearm, and hand of the seated person. These forces create a clockwise moment on the shoulder. The shoulder muscles can hold the position by generating a counterclockwise moment of the same magnitude. This sort of model provides the foundation for various biomechanical models used in ergonomics.

Biomechanical models are now available as software. Depending on preferences, these may be called computer-assisted mathematical models or computer models. Also related are mathematical models for human biological systems (see Ref. 3 for an introduction to biomathematical modeling).[3]

Another type of computer model is used for reconstructing vehicle collisions. The analyst inputs known data about roadway attributes, skid marks, weather, damage to vehicles and roadway elements, and witness testimony. The models provide outputs based on engineering computations to indicate the probable sequence of events and speeds of the vehicles. A common use is for litigation to determine fault and liability.

3.1.4 Mathematical Models

Mathematical models are used to define relationships among variables and constants. A model of the exponential growth of a population provides an example. Given the number of people in the present population (N_0) and a proportionality constant (r), the following model allows prediction of the number of people in the population (N) after a period of time (t) has elapsed: $N = N_0\, e^{rt}$.

This type of mathematical model describes a quantitative relationship between a dependent variable and a set of input variables. In this case, if the constant r is known, and values are specified for N_0 and t, the specific value of N will be determined from the calculations. However, because the model validity is based on several assumptions, the calculated N will be only be a prediction, not the precise number of people at that future time.

Statistical models are another type of mathematical model. A common use is to describe experimental results involving the effects of experimental variables on a dependent variable. These models include an error term to account for the inexact nature of the relationship. For example, an investigative team might test 10 human subjects in a laboratory to learn about the relationship between heart rate and clothing while pedaling on a stationary bicycle. The test data may be used to construct an analysis of variance model:

$$HR_{ij} = \mu_{ij} + S_{i\cdot} + C_{\cdot j} + \epsilon_{ij},$$

where HR_{ij} is the dependent variable (heart rate) of subject i in clothing condition j, μ_{ij} is the grand mean heart rate for all subjects in all clothing conditions, $S_{i\bullet}$ is the effect of subject i averaged over all clothing conditions, $C_{\bullet j}$ is the effect of clothing condition j averaged over all subjects, and ϵ_{ij} is the term to account for the variations unexplained by the other terms in the model.

The models presented above illustrate the diverse types of models used for safety analyses. Several more are described later in chapters. Equally useful are various charting methods.

3.2 USING CHARTING METHODS

Various charting methods are useful for sorting out complex systems and processes. The charting methods introduced here are process flow diagrams, organization charts, event trees, and analytical trees.

3.2.1 Process Flow Diagrams

Process flow diagrams provide a flexible methodology for modeling interrelationships among processes and order. For one common use—planning projects—project team members identify each work process they will need to complete the project. Then they organize the processes in the form of a process flow diagram. For another common use—diagramming industrial processes—these charts depict the order in which a material or product flows through the various processes from initial input to final product.

Process flow diagrams are relatively easy to develop once the processes are broken down and understood. Software is readily available and often packaged with software suites, word processing programs, and presentation software.

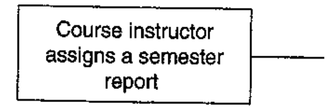

Figure 3.3 Example of a process fl

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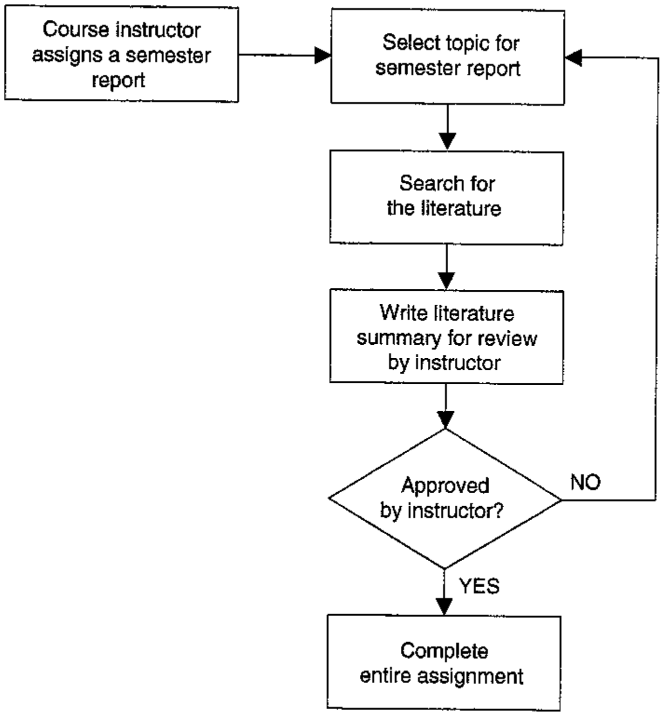

Figure 3.3 Example of a process flow diagram for a semester project report.

The most conventional arrangement for process flow diagrams is to depict flow from the top downward. Sometimes it is useful to have the flow proceed from left to right or in a mixture of directions. Occasionally, the flow is presented in a circular arrangement. The conventional symbols use rectangles to depict processes, diamonds to depict decisions, and lines with arrowheads to show the ordered flow. An example of how a process flow diagram can be used to model processes is shown in Figure 3.3. All but the first and last rectangles in the example have one input arrow and one output arrow. Other options for developers of process flow diagrams include having multiple arrows on the input side to show multiple inputs to the process and connecting multiple arrows on the output side to show multiple outputs.

A common misuse of multiple outputs from a rectangle is to show alternative paths. The correct way to show alternative paths is to use a diamond. Outputs from diamonds often involve alternative paths based on a decision indicated by text inside the diamond. The example presents the decision as a simple question calling for a "yes" or "no" answer. Diamond shapes may also be used to indicate a choice between three options by starting each option path on a corner of the diamond not occupied by an input arrowhead.

The model depicts a process in a college course. The instructor assigns students to select a topic for a semester project. The students are to pick a topic, search for relevant literature, write a description of what they found, and submit their proposal to the

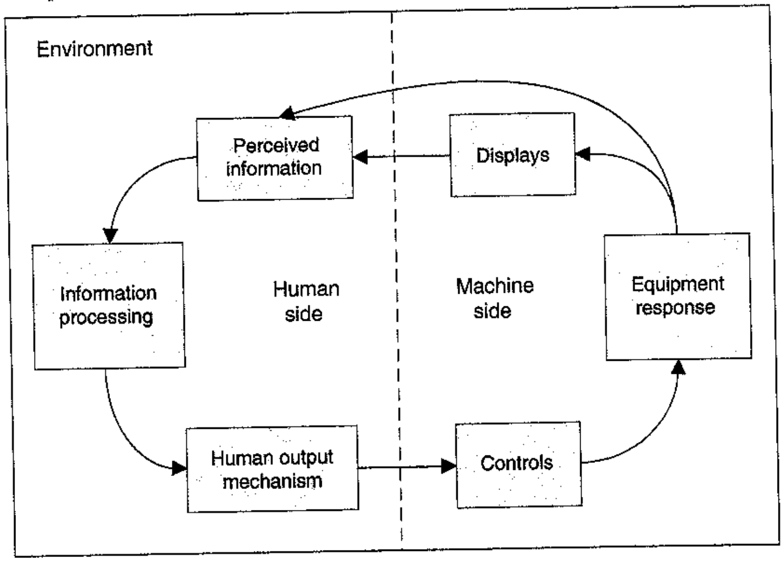

Figure 3.4 Example of a circular process flow diagram.

instructor for approval. If the proposal is not approved, the student goes back to the topic selection process, and using feedback from the instructor, develops a more suitable topic. Once the instructor approves the topic and literature review, the student proceeds to finish the project.

Many books on human factors and ergonomics contain a graphic human–machine interaction model. The authors differ on the complexity and the fine points of presentation, but agree on the overall concepts.[4] These models depict the two major components—the human and the machine—operating within an overall environment. Figure 3.4 depicts the human component on the left and the machine component on the right. Within these major components are process boxes and arrows arranged in a circular manner to depict a counterclockwise flow of processes within each major component. While a person is interacting with a machine, such as driving a car in city traffic, the person frequently repeats the cycle depicted in order to meet the ever-changing requirements for collision-free travel.

3.2.2 Organization Charts

Organization charts are top-down charts used extensively to help structure organizational management and concisely communicate the organizational hierarchy. Software for creating such charts is readily available and easy to use.

This form of chart finds use in system safety for modeling complex systems. A basic step is breaking down a complex system into units more amenable to manufacturing and safety analyses. Organizations involved in large system

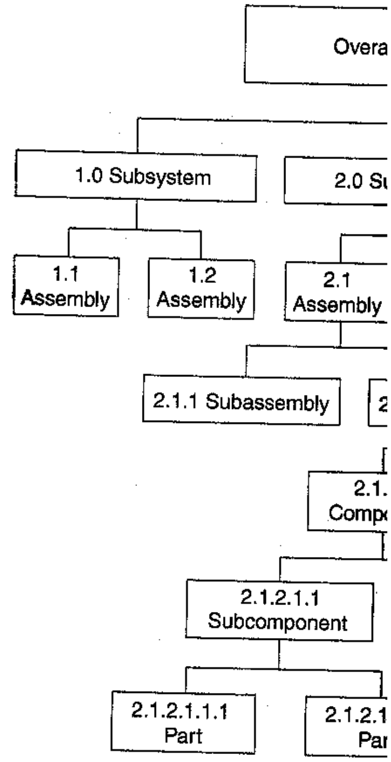

Figure 3.5 Example of an organization c

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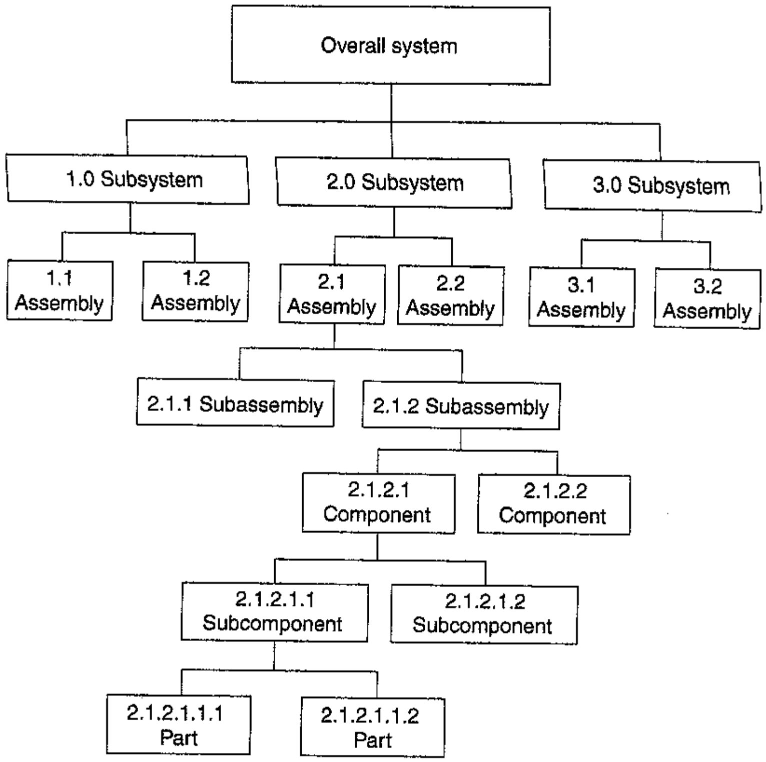


Figure 3.5 Example of an organization chart for breaking down a complex system.

development projects can make good use of organization charts when parceling out safety analysis projects and allocating resources to the subsystems and assemblies most critical to system safety and reliability.

Figure 3.5 shows a general model for breaking down a complex hardware system. It also illustrates a top-down system for numbering various units of the overall system. In the illustration, the overall system is broken down into three subsystems numbered 1.0, 2.0, and 3.0. Beneath each subsystem are assemblies numbered to indicate their parent subsystem. This systematic approach is followed in each branch as it divides into smaller units identified as subassemblies, components, subcomponents, and parts.

In system safety, the organization chart provides the format for a functional tree. A functional tree has at the top a statement of the overall system goal. Below that, the first tier breaks down the overall goal into more than one major function. The lower tiers in each branch may show the systems involved in achieving the respective function. Lower breakdowns may resemble those in Figure 3.5. Examples of function trees are provided in books on system safety.[5,6]

3.2.3 Event Trees

Event trees are tools to help analyze possibilities over time. In these charts, time progresses from left to right. These may take different forms, depending on the wishes of the analyst. Commonly, the left column indicates an undesired/initiating event. Branching moves left to right through various intermediate events, with the branches splitting at each intermediate event. Typical splits are based on answering yes or no to a simple question or indicating the success or failure of a safety mechanism. Each branch ends in the outcome described in the last column on the right.

An example event tree is shown in Figure 3.6. It applies to the foreseeable event of a roofer falling. From the initiating event on the left, the path divides at each intermediate event resulting in multiple paths. At the right of the event chart, each path ends with a likely outcome. In the example, the roofer may have been wearing a harness connected by a lanyard to a secure cable on the roof. The first intermediate event asks whether the fall was arrested by a lanyard. In that case, the first path is the top one marked "yes." The most likely outcome would be a painful experience when the fall is rapidly arrested, but no substantial injury. For the roofer who was not tied off, the second intermediate event accounts for the possibility of landing on a bush or other object that would cushion the impact. In addition, the third intermediate event allows the possibility of the roofer landing on his head/neck versus avoiding this worst-case impact position. Thus, this example event tree identifies five foreseeable paths between the initiating event and the outcome.

Event trees are also useful for following the probabilities of each path at each juncture. Examples of these are found in systems safety literature, including books by Modarres and by Ericson.[6,7]

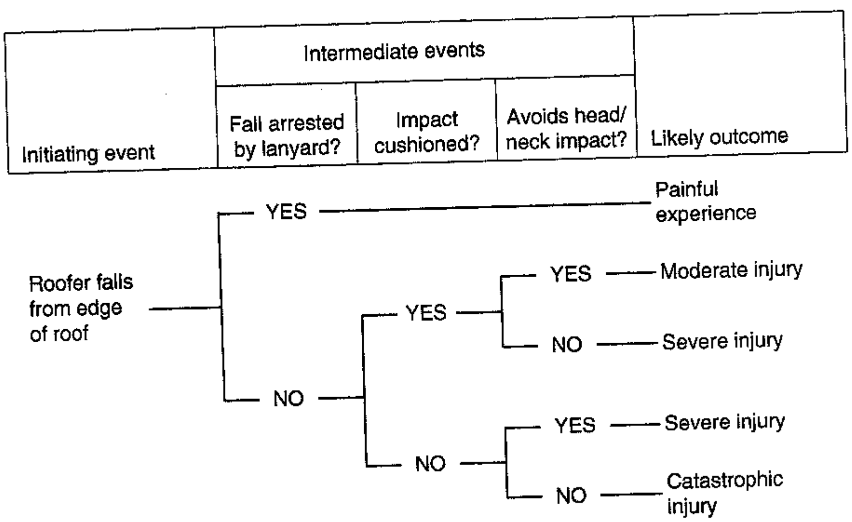
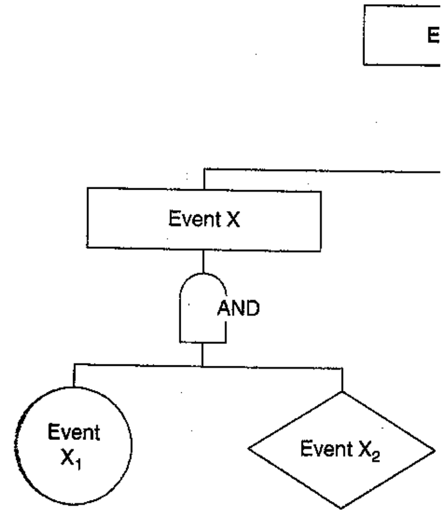


Figure 3.6 Example of an event tree.



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3.2.4 Analytical Trees

Analytical trees are charts that show logic
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The box shapes represent events or co
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event X and event Y occur. Chapters 7 and
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3.3 SUMMARY OF PART I

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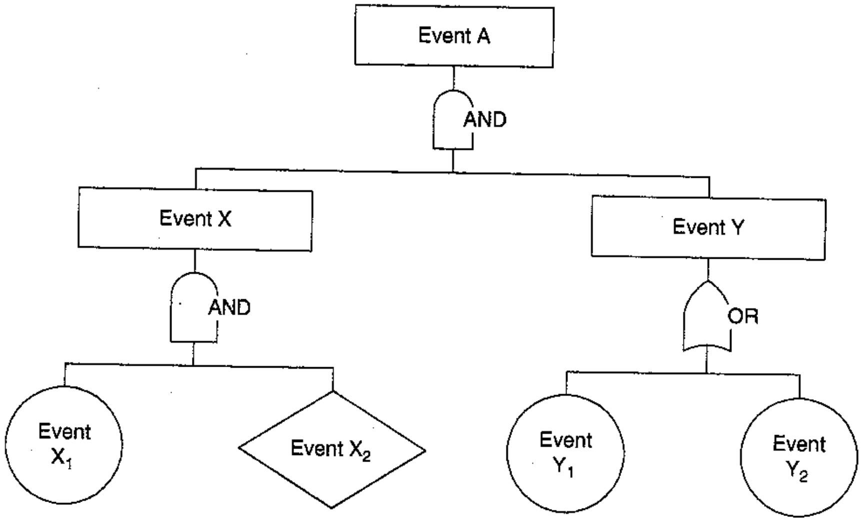

Figure 3.7 Example of an analytical tree.

3.2.4 Analytical Trees

Analytical trees are charts that show logical relationships among events and conditions. Usually, the top event is the one of greatest interest, while the lower events may be thought of as causes of the events higher in the chart. These are called trees because they resemble the shape of an evergreen tree, with the widest spread at the bottom and the narrowest at the top. Figure 3.7 shows a simple arrangement.

The box shapes represent events or conditions. Text inside the boxes describes the event or condition. Other events and conditions are indicated by ovals and diamonds. Between these boxes, ovals, and diamonds are logic gates. The most common gates indicate logical conditions that, if met, allow upward flow. For example, in the tree shown, the left-hand side branch indicates that event X will occur only if event X_1 and event X_2 occur. The right-side branch indicates that event Y will occur if either event Y_1 or event Y_2 occurs. The top event will occur if both event X and event Y occur. Chapters 7 and 8 are devoted to the most common type of analytical tree used in safety analyses—the fault tree.

3.3 SUMMARY OF PART I

The three chapters in part I provide background for the entire book. Chapter 1 introduces the multidisciplinary foundations for this book, in which traditional OSH knowledge is supplemented by concepts from system safety, public health, and educational theory. Specialists in system safety use numerous systematic methods for examining systems to anticipate hazards and find feasible means of reducing risks. Pioneers in public health injury prevention programs contributed logical ways of looking broadly at nonoccupational injuries to find risk-reduction opportunities acceptable to the public. Educators provide the theoretical structure for the end-of-chapter exercises aimed at strengthening higher level cognitive abilities.

Three important terms are discussed in Chapter 2. The first section compares and contrasts several definitions of hazard. The section ends with a proposed definition that includes a list of seven hazard sources—forms of energy, weather or geological events, conditions, chemical substances, biological agents, musculoskeletal stressors, and violent actions of people. The second section explains the three definitions of risk. It concludes that each definition of risk has utility. The third section provides the rationale for using the term risk reduction in the title of this book and in many places throughout the book.

Chapter 3 introduces several useful tools for analyzing and synthesizing systems—some of these tools are models of processes and relationships, others are charting methods used extensively in system descriptions and analyses. Many authors use these tools to enhance communication in their papers, reports, and books. Applications of these tools are illustrated in several chapters in parts II–V.

LEARNING EXERCISES

1. Find a textbook for a college course. Search the book to find a model. Models are common in economics, biology, toxicology, and engineering. If you look in a physics or engineering textbook, do not use equations found at the beginning of a chapter for your example (these are not representations of any particular system). Instead, use an example problem in which the author has described a particular situation and reduced it to a free-body diagram or analogous mechanical system.
   (a) Write a brief description of the model you found.
   (b) Indicate your view as to what type of model it is.
2. Consider the graphic relationship model for the generic user–stairway–environment interaction shown in Figure 3.1. Assume that you need to investigate an incident of a man seriously injured from falling while descending a flight of stairs. The man admitted to being distracted by a pretty woman who was ascending the stairs. Explain how you might use the model to help you think about the distraction factors in relation to other factors.
3. Make a process flow diagram to depict what a college student goes through during an academic year to secure a job when school lets out. It could be an internship position or a career position. Allow various possibilities including (1) the first interview is botched so no offer is made, (2) the second interview lands a so-so offer, and (3) the third interview leads to a fabulous offer. Include at least one process, one decision, and one feedback loop (an arrow going from a lower decision diamond back to an earlier process indicating the need to reprocess something).
4. Suppose you are asked by a power tool manufacturer to help with a comprehensive safety analysis of a new model handheld rotary power saw.

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format.
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indicating what you regard as
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You decide to start by making a functional tree using an organization chart format.

(a) Make a list of major functions suitable for the first tier of the tree.

(b) Using software available to you, make the chart with the top box indicating what you regard as the goal of a person-tool system and putting the functions in the first tier. If charting software is unavailable, you can (1) use spreadsheet software, with cells serving as the boxes in an organization chart, or (2) use the table function in your word processing software. Both alternatives can be made to look similar to an organization chart if you format the cell borders appropriately.

5. Part I of this book has three chapters. What was the rationale for grouping these topics into a unit called part I?

6. For supplemental reading on the use of modeling for safety analyses, an article by Pat Clemens is recommended.[8] He explains how models are used in system safety and provides a critical commentary on sloppy practices.

(a) When he talks about "fidelity" of a model, what does he mean?

(b) Explain his analytical progression of models based on the degree of fidelity.

(c) What sloppy practice does the article author consider most pervasive?

(d) Near the end of the article, Clemens provides advice for minimizing the effects of the errors and assumptions from modeling. Briefly list the items of his advice.

TECHNICAL TERMS

Analytical trees	Charts for analyzing systems using probability and other mathematics.
Event trees	Charts for showing how a specified event can result in multiple paths leading to different end points.
Graphic relationship models	Two-dimensional or three-dimensional depictions of the elements in a system and their interrelationships.
Mathematical models	Generic equations relating variables and constants under various assumptions.
Models	Representations of systems.
Organization charts	Two-dimensional arrangements for depicting the hierarchical structure of units within an organization.
Physical models	Three-dimensional physical constructions made similar to the actual system represented.
Physics models	Generally, simplified drawings representing the variables in an equation paired with the drawing. Some common variables are objects, vectors, time, and distance.

Process flow diagrams	2D graphics showing order of flow among processes and decisions.
Statistical models	Equations to explain relationships among specified variables, including unexplained variability known as error.

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art II

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II contains five chapters about an
reduction. Chapter 4 describes jo
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tions. Extending job hazard ana
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