CHAPTER 16

Engineering Analysis

INTRODUCTION

Analysis is the breaking down of an object into its basic elements to get to its essence. This process is a means of studying the nature of something and identifying its essential features and their relationships. Analysis is the opposite of synthesis, which is identifying common features in separate entities. The tools for analysis are based upon logic and the application of logical systems (e.g., mathematics, physics and mechanics). The role of analysis in design is a critical one and can be considered the internal guidance system of a project. A project without analysis is like a sports team without a coaching staff or a ship without a rudder.

The Role of Analysis

A focus of this section is to explore the relationship between analysis and other elements of design. The list of questions and topic areas below address the role of analysis in engineering:

- The traits of engineers and their relationship with analysis.
- What comes first: analysis or experience?
- At what point in the evolution of a design should the guidance from theory be given priority? Guidance from experiment?
- The seamless interplay between hands-on and theoretical components.
- Will the application of the tools of engineering remain static?
- What happens when theory and experiment do not agree?
- How is it known that an analysis is flawed?
- How is a design analyzed?
- What are the types and levels of analysis?
- Where does analysis begin?
- Does a project ever begin based solely upon analysis?

- Try to think of a situation where analysis is the very last thing done.
- List a few examples of the critical role that analysis has played in engineering design.

THE TRAITS OF ENGINEERS AND THEIR RELATIONSHIP WITH ANALYSIS

Engineer Traits

Gibney [1] considers the creative process in the context of improving abilities to generate fresh approaches and products. She reviews four educational programs working in this area, including work in progress at Stanford University by R. Faste, where engineers are encouraged to use “ambidextrous” thinking, or both the left and right hemispheres of the brain. Linear, logical processes and verbal abilities derive primarily from the left side of the brain, and visual-spatial properties, intuition and qualitative assessment skills derive primarily from the right side. An eventual goal as an engineer’s skill evolves is to move towards “whole brain” thinking.

Often, first-year students have significant analytical or creative skills, but have not yet developed the broad set of abilities needed in engineering. University goals are to nurture existing talents as well as to broaden the range of talents. Engineering graduates should have an integrated knowledge of their profession, viewing sub-disciplines and engineering tools as problem-solving resources. Engineers should respect the need for complementary talents in the design process. This respect should naturally extend to other engineers and team members who will typically possess valuable abilities in disparate areas. Figure 16.1, a conceptual figure summarizing these thoughts, indicates initial focus and an idealized broadening of capabilities.

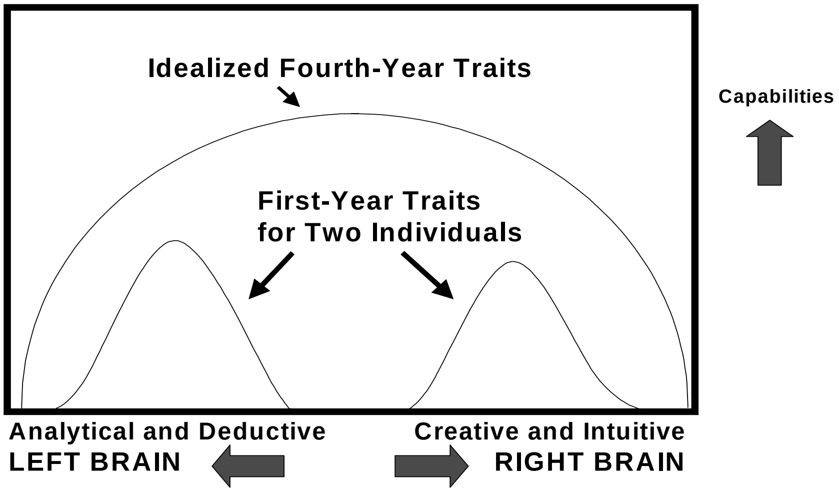


Figure 16.1. First-year vs. fourth-year traits of engineering students.

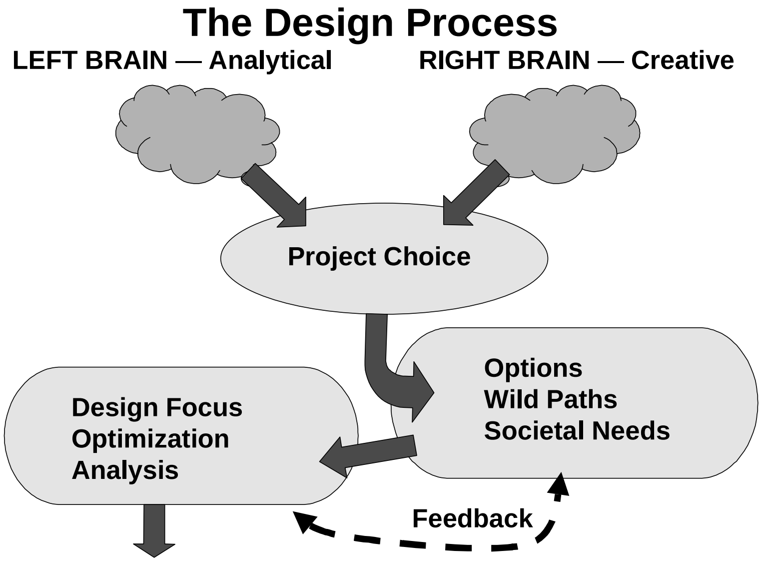
Two individuals with such focused talents early in their careers will complement one another quite well. Most people will have far more complex distributions of talents than this extreme example. An important moment in the process of improvement is identifying and admitting the need to fill “ability gaps.”

Thus far, this section has discussed analysis in the context of traits and abilities—a philosophical approach. Next, a more practical perspective is taken, in the context of the design process.

THE ROLE OF ANALYSIS IN THE DESIGN PROCESS

Complementary Roles

The design process requires different abilities and perspectives at various stages. Several models of this process presented here derive from different engineering disciplines or viewpoints. Though the modes of presentation differ, the fact that the process described is almost identical should give confidence that these models capture the basic elements of the evolution of designs. The diagram in Figure 16.2 captures the design process and considers the complementary roles of different traits of engineers.



igure 16.2. The design process, with consideration of the complementary roles of different traits of engineers.

This flow diagram follows the design process in emphasizing how traits derived from both the left and right hemispheres of the brain have critical roles at different times. In the beginning, either or both perspectives can drive the choice of a project. Even this initial choice may require fine-tuning as the sequence of steps continues. The following stage is one where creative brainstorming suggests paths to be investigated. The next stage involves a critical assessment of the possibilities and a first level of analysis, usually resulting in a prioritized list of choices and rational. After this first crack at analysis, there is typically some iteration and another review to make sure additional avenues are considered. Usually, a clear design focus is an outcome of this part of the sequence.

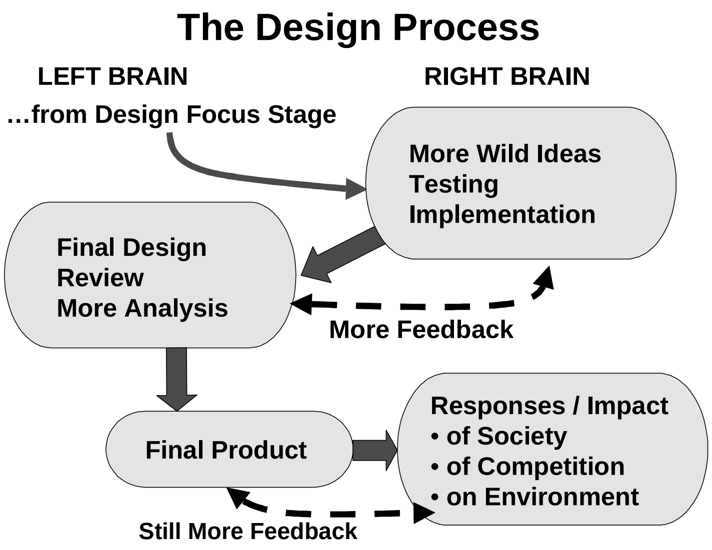


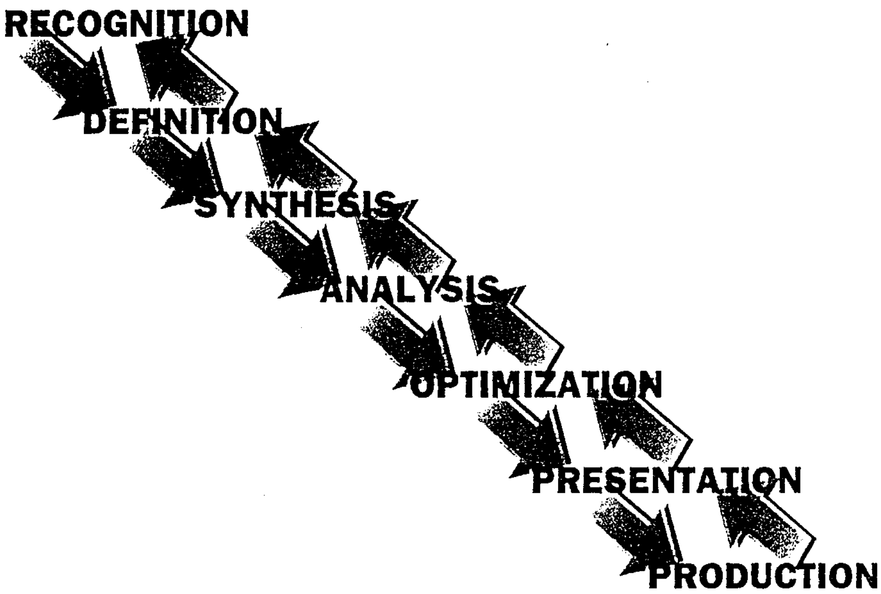
Figure 16.3. The design process continues with iterative stages involving prototypes and final product design.

Next (see Figure 16.3), a creative review of the ways of constructing, testing and implementing the design usually leads to a prototype, or frequently prototype*s*. This part of the process is more open to new approaches before the design and test results are critically reviewed and analyzed. The elements of the final design—together with recommendations for production, use and marketing—are a key product of this review phase. Again, there is an opportunity for iterative fine tuning to make sure key innovations are incorporated.

Even after the final product is produced, there exists a continual need to monitor the responses to and impacts of the product. A minor design flaw might show up during use, and a small change in materials might make the product safer to use or more friendly to the environment.

An Iterative Process

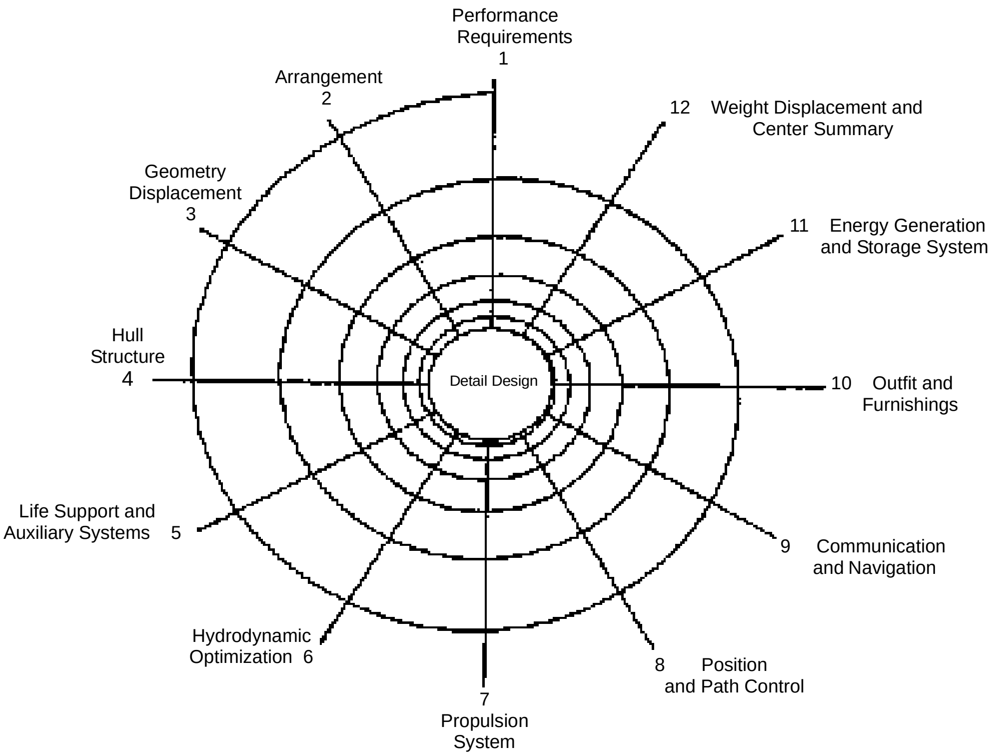
Radcliffe [2] presents an alternate view of the design process, which is illustrated in Figure 16.4. This sequence diagram emphasizes the iterative nature of the process. Since new information or a new insight can be discovered at any stage, it may be necessary to return to a previous point in the process. Although Radcliffe adds a problem recognition and a presentation stage, the sequence is quite similar to that presented in Figure 16.2 and Figure 16.3.



igure 16.4. Stages in the design process: Several iterations through multiple steps are often required before arriving at a successful design. Source: Radcliffe [2].

The Design Spiral

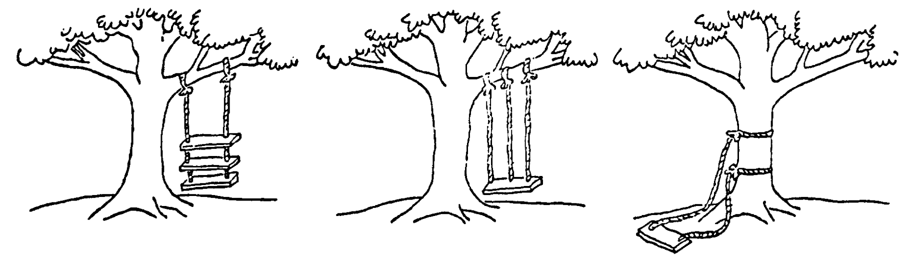
Designing a submarine is an especially challenging project. There are constraints of size and weight, environmental challenges (depth and pressure), critical life support needs, hull design, mission requirements, as well as propulsion and energy requirements. Decisions on each of these elements can greatly impact all or many of the other elements. Submarine engineers have developed the design spiral as a model to ensure that the various elements integrate in a methodical way [3]. This process, reproduced schematically in Figure 16.5, helps to ensure that the strong interactions between sub-components are accounted for at all stages. As one moves from the outside of the spiral to the inside each of the systems is re-visited in an interactive way, moving toward the final design. Other complex systems—such as aircraft, space vehicles and chemical plants—offer similar challenges in which each of the components explode into a design process embedded in a larger one demanding tremendous care in integration. Analysis is the umbrella that protects the total system—tying everything together and ensuring that a minor change in one sector of a design does not cause a disaster in another.



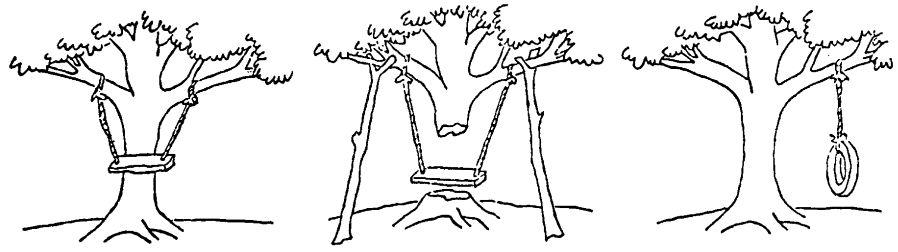
igure 16.5. The “design spiral” model of the design process helps submarine engineers ensure that all design elements integrate in a methodical way. Source: Allmendinger [3].

Design Definition

Dieter [4] presents an interesting set of final designs (see Figure 16.6) to emphasize the importance of the definition of the design problem. This figure also shows how critical an integrated and well-coordinated design process is to a sensible outcome.



As proposed by the project sponsor As specified in the project request As designed by the senior designer



As produced by manufacturing As installed at the user's site What the user wanted

Figure 16.6. Note how the design depends on the viewpoint of the individual who defines the problem. Source: Dieter [4].

CONTINUITY BETWEEN THEORETICAL & HANDS-ON ENGINEERING

During the design process, there should be a seamless transition between theory and experiment. An effective engineer respects and understands the relative roles of analysis and practice. An engineer should feel not only comfortable and competent in both areas, but also in transitioning between them. With experience, the choices and application of engineering skills should become a reflex. As students move through their academic careers, the critical roles of the analytical components of their courses become clear.

EVOLUTION OF ENGINEERING ABILITIES

The evolution of skills should not be limited to an academic career, but be a life-long process. There are many examples of scientific breakthroughs having such far-reaching implications that entire disciplines changed “overnight.” The transistor is one such example, which challenges traditional electrical engineers to adapt. If one is alert to the implications of change, times of rapid transition are also times of exceptional opportunity. These comments apply to both theoretical and experimental skills and should be a strong incentive to invest in continuing education.

INTERPLAY BETWEEN THEORY AND EXPERIMENT

Questions often arise when comparing theory and experiment, and it is not always clear where to place your confidence. Table 16.1 contrasts the typical sequence of elements involved with a theoretical development and an experiment. This should be helpful in contrasting the two approaches of investigation. Analysis is a critical element of both.

Table 16.1. Typical Developmental Sequences.

Theory	**Experiment**
Definition of the Problem	Definition of Goals
Assumptions	Choice of Parameters
Initial Conditions	Analysis of Approaches ◆ Full Scale ◆ Scale Model
Boundary Conditions	Choice of Methodology ◆ Sensors ◆ Processing
Approach ◆ Analytical ◆ Numerical	Analysis of Error
Presentation	Presentation
Conclusions	Conclusions
Range of Applicability	Range of Applicability

Evaluation

Important questions arise when theory and experiment are not in agreement. There are key areas to investigate when critically assessing the results of theoretical developments or experiments. The table below lists valuable areas to use for the evaluation of theoretical and experimental results.

Table 16.2. Evaluation areas for theory and experiment

Theory	**Experiment**
Validity of Assumptions, Initial Conditions and Boundary Conditions	Accuracy of Measurements
Reasonableness of Any Extrapolations	Reasonableness of Any Scaling
Error Free Analysis	Repeatability of Measurements
Resolution of Phenomena is Appropriate	Difficulty in Execution

Varied Approaches

There are also many theoretical and experimental approaches that can be taken. These vary greatly in cost and complexity and should be chosen to be appropriate to the goals of the investigation. At times, a rough estimate, a simple qualitative experiment or a demonstration answers key questions. Such “quick and dirty” estimates can give guidance or assurance at critical phases of an investigation. The fact that an approach is shown to be plausible and is not discounted can justify the expenditure of additional time and energy.

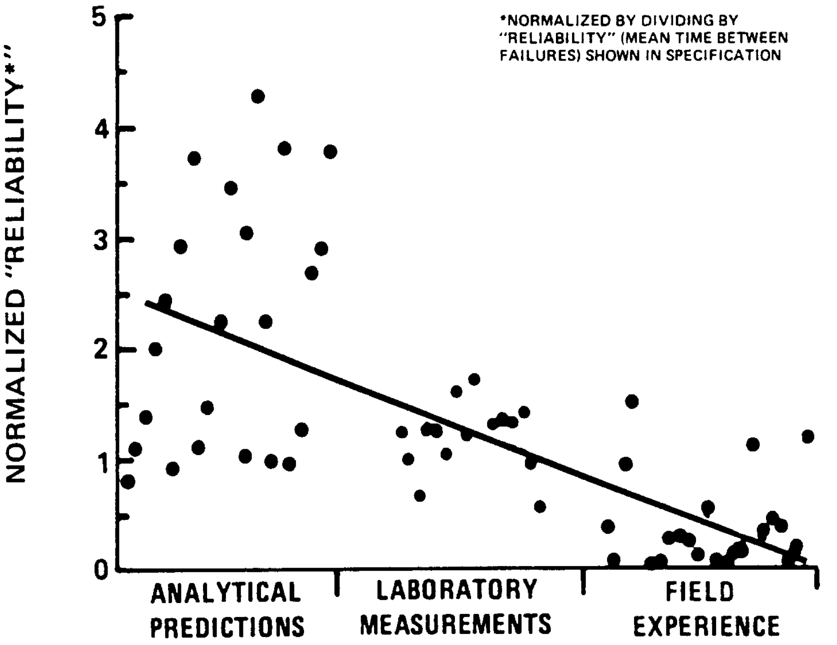
On the other hand, there are situations where in-depth calculations and/or experiments are appropriate. This could be when important, but small, differences are an issue, or when a critical decision requires a detailed justification. Often, the extent of the study required falls between these two extremes. Table 16.3 lists some of the possible analytical paths to answering questions.

Table 16.3. Paths to answering questions during the design process.

Types of Theoretical Analyses	**Types of Experiments**
Order of Magnitude Analysis	Simple Qualitative Experiment
Rough Estimate	Scaled Experiment
Limited Analytical Development	Limited Experiment
Complete Analytical Solution	Full Scale Experiment
Numerical Calculation	Exploratory Experiment

Often the short, “back of the envelope” estimates apply during the early stages of projects, with more detailed studies undertaken during the critical decision-making stages. Frequently, near the end or execution stages of a project, there may be a need to resolve a particular issue. At this final point, questions and problems usually can be clearly stated.

In Figure 16.6, Augustine [5] indicates the danger in relying upon initial estimates of the functioning of designed systems. Note that the actual field experience is several times worse in terms of reliability than the initial analytical estimates. This presentation would probably have looked just as gloomy if the initial estimates were based upon lab measurements alone, prior to the final design evolution. This also reinforces the need for an iterative process using complementary techniques.



BASIC DATA SOURCES:
(1) G. KERN, "OPERATIONAL INFLUENCES ON AVIONICS RELIABILITY."
(2) DEFENSE MANAGEMENT JOURNAL, "7 MID 70's SYSTEMS."
(3) AUTHOR'S DATA COLLECTION

Figure 16.7. Inability of hardware to withstand real world pressures. Source: Augustine [5].

THE ANALYSIS PROCESS

Previous sections discussed the many facets of analysis, but have not addressed the basic methodology used in performing analyses. Analysis involves more than using something learned in a math, physics or dynamics course, although the insights and tools provided by such courses are indispensable. The efforts involved with a typical analytical study are summarized below. These steps can be informal or quite formal, depending upon the scope or importance of the effort.

A typical sequence of efforts for analysis of a device or problem:

- Conceptually break down into component parts.
- Define purpose or function and desired capabilities.
- Represent components in physical or mathematical terms.
- Investigate whether or not the intended purpose is fulfilled by your logical representation (will it work?).
- Explore how parts interface and become something complete (a functional whole).
- Provide guidance concerning impact; e.g., implications, indicated changes and improvements.
- Document the details and essentials of the analysis.

THE CRITICAL ROLE OF ANALYSIS IN ENGINEERING PROJECTS

Petroski [6] makes a point about how cautious engineers need to be during the design stage. In fact, he suggests the advantage of at least slight paranoia and imagining that the impossible will happen to a creation. It is essential to learn from failures as well as successes. Successes and failures (see Table 16.4) show that we can derive valuable lessons by analysis of a great range of designs, as described below.

Table 16.4. Engineering design successes and failures.

Successes	**Failures**
Radar	Tacoma Narrows Bridge
Stay-on Tabs for Aluminum Cans	Kansas City Regency Hotel
Boeing 777 Aircraft	Challenger Space Shuttle
Global Positioning System	Three-Mile Island Nuclear Power Plant

Some past engineering failures involved a history of designs following a methodology that seemed to work. However, when scale sizes or loads were extended and the designs subjected to environmental extremes, the result was numerous historical failures to analyze and learn from.

Conversely, when analyzing a design that works and has been accepted for long periods of time by a large segment of society, there are also valuable lessons to be learned. In this spirit, a review of several successful designs offers lessons worth emulating. Following this, a review of several failures will identify paths worth avoiding.

Successes

The development of radar (RAdio Detection And Ranging) required an existing base of electronic capability to be feasible. This is a case where the supporting technology grew to a threshold that made radar possible. This development eventually led to parallel remote sensing devices using light (lidar) and sound (sonar and sodar). It took more than 30 years for these variations to appear. As illustrated in this example, a successful design exploiting one area of technology may have many fruitful derivative applications in other disciplines.

The stay-on tabs for aluminum cans that are standard now are an example of the value of being sensitive to a societal need and acting upon it. These tabs replaced throw-away tops that were wasteful and created pollution. About a trillion stay-on tabs have been produced thus far, saving more than 4 million tons of aluminum (recovered and recycled). This is an example of a simple concept having great impact.

The Boeing 777 aircraft is an example of a different type of success. The efficient and cost effective design was possible not just because of the development and application of advanced computers and software, but also because networking permitted engineers world-wide to work effectively on the same design. This demonstrated the feasibility of paperless design and concurrent engineering.

The development of Global Positioning System (GPS) technology is an example of an existing base of infrastructure and technical capabilities making a concept practical. In this case, satellite platforms and electronics enabled the execution of the concept, permitting accurate location (to within meters) world-wide. Uses for this capability continue to be discovered. This is an example of an area that is in a stage of dynamic expansion of applications. It continues to be fruitful to analyze the system and search for additional uses.

Failures

The Tacoma Narrows Bridge collapsed in 1940 when exposed to relatively modest winds exciting a resonance. This is an example of extrapolated engineering, where the effects of winds were not properly considered. This example of an engineering design failure should encourage caution when extending past, seemingly successful, designs.

The walkways at the Kansas City Regency Hotel gave way in 1981, resulting in many deaths. A seemingly non-critical design change to save time and cost resulted in creating a weakness in the suspension. As illustrated by this example, there is no such thing as an unimportant design element—all details need to be considered at all stages.

The Challenger space shuttle exploded on January 28, 1986. Tufte [7] provides details of the analyses that explained the cause of the disaster that involved O-ring seals failing at low temperatures. The seals were critical elements to the sections separating different rocket stages. The decision to use multi-stages was a political one designed to make use of a vendor from a different state. A single stage would not have been possible to transport. This decision made the design more complex than necessary, which eventually led to a failure. The investigation was notable in that the reason for the failure was clearly communicated to the media using a simple, but elegant experiment illustrating how the failure occurred.

The Three-mile Island nuclear power plant failure provides an example of how a simple component can cause a major problem, also indicating the importance of working out foolproof displays of system status. The problem was that a valve failed causing an overheating problem. However, the visual display did not indicate the actual status of the valve, but rather what the valve had been “told” to do. Such attention to displays is critical for engineering systems in which operators monitor status and make decisions.

As suggested by the above examples, there is a vast body of design lessons and guidance to be gleaned from the analysis of successful and failed designs.

CONCLUSION

The intent of this review of engineering analysis is to engender appreciation of the role analytical assessment plays in the design process. To really appreciate the importance of this role, engineers need to apply analysis in their day-to-day work and experience the results over a period of time. Analysis is the essence of being an engineer. The ability to analyze distinguishes an engineer from a technician.

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