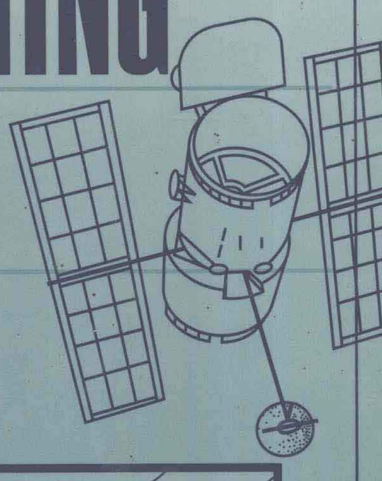
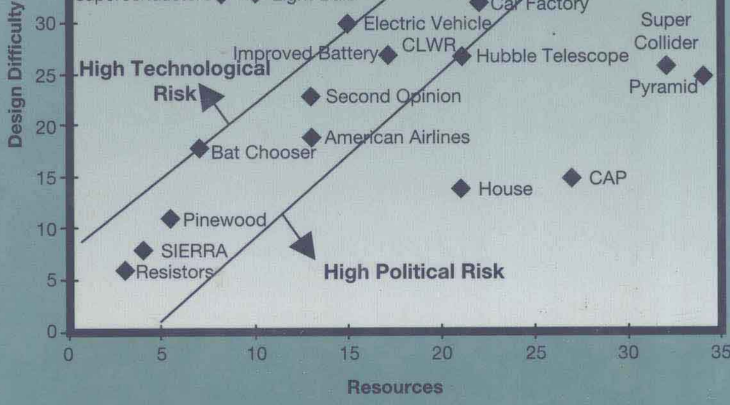
Metrics and Case Studies for Evaluating Engineering Designs





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PREFACE

This book presents metrics designed to assess the design difficulty, required resources, systems engineering efficacy, and developmental environment for system design. We think that creating metrics to assess the engineering design process is very important. As Harrington (1991) put it, "Measurements are key. If you cannot measure it, you cannot control it. If you cannot control it, you cannot improve it. It is as simple as that."

First we present two simple metrics: Design Difficulty and Required Resources. Then we present case studies to show how these metrics can be used. Several of these designs were done by our group. The advantage of this is that we can point out the mistakes that we made. The first score of case studies is simple. Creating them taught us two things: formal systems engineering is seldom used on small projects, and these simple metrics can be used to detect projects that will have high technological risk or high political risk. The metrics presented in the first part of the book, Chapters 1–23, are simple and general. We think each company should develop its own metrics that are tailored to its organization.

The second half of this book, Chapters 24–34, is devoted to metrics for systems engineering efficacy and the developmental environment for system design. The first chapter of this part of this book is entitled "What is Systems Engineering?" Bahill has delivered this lecture dozens of times. At the end of each lecture, someone comes up and suggests a different title. Project managers say, "What you have just described is really Project Management." Quality engineers say, "You have just described Quality Engineering." People who have served as Lead Engineers on projects say,"You have just described the job of a Lead Electrical Engineer." Design engineers say it describes design engineering, etc. The point is that many different types of people do systems engineering and all good engineers do systems engineering. So in this book we often use the term *Systems Engineer*. The reader may substitute any other desired term. It is not important what it is called; it is only important that all of the tasks get performed.

The last six case studies in this book show how to use our complex metrics. All these case studies are airplane development examples, so the design process is similar. They show that successful systems can be developed if there is good systems engineering and a good developmental environment. We hope that they illustrate good and bad systems engineering principles. They should also show that the systems engineering process can be measured and monitored; because if you can measure and control it, then you might be able to improve it.

We thank the following students at the University of Arizona who studied these cases and made comments that are included in this book: Bo Bentz, Brian Croyle, Jeremy Duke, Cassie Fleetwood, Allan Jaegers, Bill Karnavas, John Kneuer, Gary Knotts, Dennis Shephard, and Eric Taipale. We also thank Bruce Gissing, retired Vice President of Operations for the Boeing Company, for his helpful comments.

REFERENCE

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CONTENTS

1

DESIGN DIFFICULTY AND RESOURCES METRICS

INTRODUCTION

The ability to create technical designs quickly, accurately, and cost-effectively makes companies successful. It is important for companies to understand the process for designing technical systems. There are many books, short courses, standards, handbooks, and manuals that explain various facets of the system design process. In addition, we think that studying examples of successful and unsuccessful design efforts will help engineers assess the feasibility of design projects for their companies. We present metrics that can be used to assess risk of project failure. Then we present case studies to show how the metrics are used. We propose that such case studies and metrics can be developed by other companies as appropriate for their products. Thus we hypothesize that engineers can develop company specific metrics for the quantitative assessment of design feasibility. For example, Figure 1-1 shows the four regions

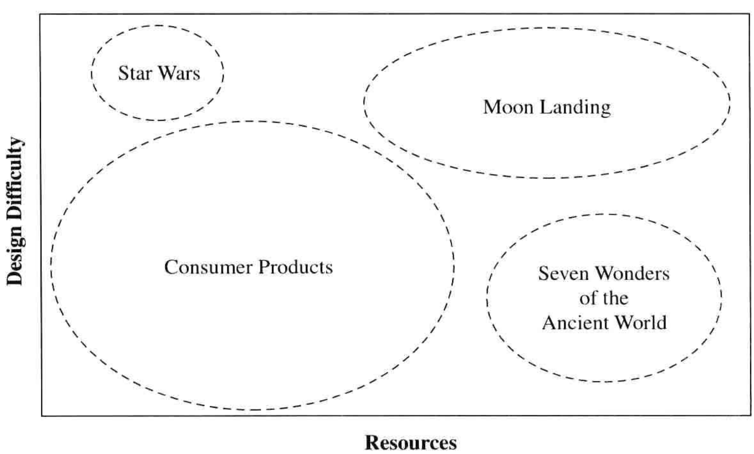

Figure 1-1 The four regions of the Design Difficulty versus Resources plane.

that our case studies encompass. If a small consumer products company was asked to design and build a system that fell into the Star Wars region, the systems engineer should be able to determine that there is virtually no feasibility of this design effort succeeding.

CASE STUDY APPROACH

Through the use of case studies, we can create a bridge between systems theory and actual design efforts. Figure 1-1 compares the design difficulty versus the resources used to create the designs. To set a common limit, we have decided that the system design process ended when the first production unit was built. The areas named reflect the type of design needed. The largest area, Consumer Products, is characterized by a design difficulty that is small to moderate and requires a small to moderate amount of resources. One area that requires the maximum amount of resources, Seven Wonders of the Ancient World, has a design difficulty that is small to moderate. The upper left quadrant is called Star Wars after the 1977 movie. It indicates items that we can imagine, but probably not design and build because of the complexity of the product. The designs are so difficult that it is impossible to solve these problems; thus they remain intractable. The final region is for high design difficulty coupled with massive resources. This quadrant is called Moon Landing to indicate the enormous nature of both the design effort and the resources needed.

The values for design difficulty and resources were computed by summing scores for their constituent parts. Each constituent part is an ordinal ranking within the category. We recognize that ordinal rankings are not necessarily additive, however in this case, we have adjusted the categories so that the answers pass a reasonableness test. Extreme examples may not fit these rankings; this scale fits these specific case studies, although it is not an unassailable system.

DESIGN DIFFICULTY

The scores for the vertical axis of the graph, Design Difficulty, represent a combination of the following categories:

1. design type, which is a continuum from redesign to original innovative design and, finally, to breakthrough design,
2. complexity of the knowledge needed to create the design,
3. number of steps needed to complete the design,
4. quality implementation effort,
5. process design, and
6. aggressive goals for selling price.

Each case study was scored using the scale illustrated in Table 1-1. Many more categories can be created. For example, we found that the expected system life was another useful and orthogonal metric, but we chose not to incorporate it here. We decided to derive a minimal set that would be useful for engineers embarking on a new design project.

By choosing ranges for these categories we have, in effect, created weights of importance for each.

A. **Design type** reflects whether feasible solutions exist and how much original thought goes into the project.

14 or 15 points are given for a breakthrough design effort.

7-13 points are given for original innovative design.

0-6 points are given for continuous improvement.

B. **Knowledge complexity** needed to create the design is based on an estimate of the number and availability of the people with the necessary knowledge to do the design.

9 or 10 points are given for undiscovered knowledge that can be found only by specialists.

6-8 points are given for complex knowledge held by few people.

3-5 points are given for complex knowledge held by numerous people.

0-2 points are given for common knowledge held by many people.

C. The number of **steps** is defined as the number of major process steps that are needed to assemble the system. It is related to the number of major components.

9 or 10 points are given for systems with greater than 10,000 steps or components.

5-8 points are given for systems with more than 500 but less than 10,000 steps or components.

TABLE 1-1 Design Difficulty Scores.

Metric	Range	Score
Design type	0-15	
Knowledge complexity	0-10	
Steps	0-10	
Quality	0-10	
Process design	0-5	
Aggressive selling price	0-5	
Design difficulty total	0-55	

3 or 4 points are given for systems with up to 500 steps or components.

0-2 points are given for any system with fewer than 50 steps or components.

D. **Quality** represents the desired level of quality in the product. It could come from the customer's inherent expectations or it could be enhanced by the company. It could be quantified with defect rate, reliability, maintainability, etc. Evidence that the company is serious about quality includes programs such as Zero Defects, Six Sigma, total quality management (TQM), ISO-9000, the Baldridge Award criteria, quality circles, gathering customer feedback, Taguchi methods, Quality Function Deployment (QFD), and Deming's 14 points. But be aware of Deming's 10th point: "Eliminate slogans, exhortations, and targets for the work force asking for zero defects and new levels of productivity. Such exhortations only create adversarial relationships, as the bulk of the causes of low quality belong to the system and thus lie beyond the power of the work force."

7-10 points are given for a system whose developer places high emphasis on implementing or continuing quality-related programs and techniques on the system development effort.

4-6 points are given for a system whose developer places medium emphasis on implementing or continuing quality-related programs and techniques on the system development effort.

0-3 points are given for a system whose developer places little or no emphasis on implementing or continuing quality-related programs and techniques.

E. **Process design**: is crucial because Systems Engineering designs both a product and a process to manufacture it. Sometimes the design of the process adds to the difficulty of the design of the product. Difficulty in designing the manufacturing process includes the **complexity** of the fabrication processes and the **quantity** of items produced. For example, the manufacturing process to produce one or a few large, complex systems can be as extensive as those established to mass produce small, less complex systems. Quantity is normalized between different items by partly basing the measure on the extent of national market share met by the output of a system's manufacturing operations.

5 points are given for highly complex manufacturing operations that are designed to produce systems in quantities to meet a large national market share.

4 points are given for:

1. highly complex manufacturing operations that are designed to produce systems in quantities to meet a moderate national market share, or
2. manufacturing operations of moderate complexity that are designed to produce systems in quantities to meet a large national market share.

3 points are given for:

1. highly complex manufacturing operations that are designed to produce systems in quantities to meet a small national market share, or
2. manufacturing operations of moderate complexity that are designed to produce systems in quantities to meet a moderate national market share, or
3. manufacturing operations of low complexity that are designed to produce systems to meet a large national market share.

2 points are given for:

1. manufacturing operations of moderate complexity that are designed to produce systems in quantities to meet a small national market share, or
2. manufacturing operations of low complexity that are designed to produce systems in quantities to meet a moderate national market share.

1 point is given for manufacturing operations of low complexity that are designed to produce systems in quantities (of greater than one unit) to meet a small national market share.

0 points are given for manufacturing operations of low complexity that are designed to produce only one system.

Note: This is not a good metric by itself, because it is dependent on other metrics: design type, complexity of knowledge, number of steps, and quality.

F. **Aggressive** goals for **selling price** is the degree to which the system design is driven and constrained by unit sales price requirements or goals. These requirements and goals are based on the competition level in the market. In general, the greater the competition, the greater the constraint. The sales price requirements and goals for government systems can be determined by design-to-cost requirements or goals, as well as by the existence of equivalent commercial systems already on the market.

4-5 points are given for very challenging unit sales price requirements or goals driven by a highly competitive market.

2-3 points are given for moderately challenging unit sales price requirements or goals driven by a moderately competitive market.

0-1 points are given for little or no challenge to meet unit sales price requirements or goals due to lack of competition or lack of unit sales price requirements or goals.

Note: Aggressive goals for time to market might also be a useful metric. Reducing time to market will increase profit and will make the design more difficult.

The scores are provided in a table at the end of each case study similar to that illustrated in Table 1-1.

RESOURCES

The scores of the horizontal axis of Figure 1-1, Resources, represent a composite score of the following categories:

1. costs to develop the product through the first production unit,
2. time from the beginning of the effort through the first production unit, and
3. infrastructure required to complete the design.

The score for each case study is on the scale illustrated in Table 1-2.

A. **Cost** is the amount needed to pay for development, including salaries, utilities, supplies, and materials, through the first production unit. This is not in absolute dollars, but in terms of the payer's ability to pay. For example, the Internal Revenue Service may consider a Cray computer to be low cost, but you or I may consider a Pentium PC to be expensive.

14 or 15 points are given for massively expensive systems requiring major sacrifices.

9-13 points are given for very expensive systems that are rarely developed.

3-8 points are given for moderately expensive systems.

0-2 points are given for affordable systems.

Note: This metric considers only design and manufacturing costs. Another interesting metric would be total life cycle cost.

B. The **time** score is for time spent from the beginning of the effort to define the customer's needs through the first production unit.

10 points are given for more than eight years.

8 or 9 points are given for five to eight years.

4-7 points are given for one to five years.

3 points are given for six months to a year.

TABLE 1-2 Resources Scores.

Metric	Range	Score
Cost	0-15	
Time	0-10	
Infrastructure	0-10	
Resources total	0-35	

2 points are given for three months to six months.

1 point is given for one to three months.

0 points are given for less than a month.

C. **Infrastructure** required to achieve the design is also hard to quantify. Infrastructure is described as the physical resources needed for construction (including machine tools, process shops, and assembly workstations), transportation, communication, utilities, laws and legal protections, skilled managers, and the education system available. Infrastructure must be judged in regard to the designer's ability to get and use the infrastructure over the needed design time.

Infrastructure is relative to the time the system was designed. Thomas Edison did not need a lot of scientific support. He invented everything he needed, like the world's first good vacuum pump. So he has a low infrastructure score. The Apollo program used every available engineering tool. We gave it the maximum score for infrastructure. In contrast, the Boeing 777 used vastly more complex computer aided design tools, but we did not think they pushed the limits of availability, so we only assigned that project an 8.

9 or 10 points are given for a massive infrastructure requiring major portions of the available labor force and the available equipment.

6-8 points are given for large complex infrastructures requiring large portions of the cost of the entire project

3-5 points are given for moderate infrastructures requiring people on the project to support it.

0-2 points are given if it is a common, low cost infrastructure (e.g., clean tap water in the U.S.)

The scores are given in a table at the end of each case study similar to that illustrated in Table 1-2.

All of our metrics depend heavily on the context of the design. It is impossible for a person in a primitive country to obtain the resources necessary to build a telephone in a reasonable time. However, it is relatively simple to do this in America. It may be impossible for a small company to obtain $10 million to fund a new product. But it is easy for General Motors. At the end of every case study, the context for the scores will be given to help explain the rational for the given scores.

CASE STUDIES

In the following paragraphs, we give a brief description of our first case studies. References and a full discussion are given in subsequent chapters.

1. Resistor Networks—A network of up to four resistors connected in series and/or parallel must be designed to produce a specific resistance value.

2. SIERRA Train Controllers—University students have developed numerous versions of a controller to run two HO gauge model trains. The controller must prevent collisions and can be built with three to six state designs. Despite being limited to nine components, students have found dozens of successful solutions.
3. Bat Chooser—Bat Chooser is a small consumer product developed to determine the Ideal Bat Weight for an individual baseball or softball player. By measuring the swing speed of a given bat, the ideal weight of bat for the player can be calculated.
4. Pinewood Derby—A Pinewood Derby is a Cub Scout race of wooden cars. Creating schedules for these races was a difficult problem.
5. Second Opinion—Second Opinion is a personal computer based decision support system that helps with the diagnosis and prognosis of young children who may have begun to stutter.
6. American Airlines Scheduling—American Airlines schedules its aircraft and crews using computer algorithms. These sophisticated algorithms search for a good solution, but not necessarily the optimum solution.
7. Superconductors—Superconductors are materials that exhibit no electrical resistance when very cold. Recent development of advanced copper oxides was a breakthrough design effort. In four months, Paul Chu of the University of Houston raised the world record from 30° K to 90° K.
8. Incandescent Light Bulb—In 1879 Thomas Edison developed the first commercially viable light bulb. He was ridiculed throughout the effort by the mainstream press, engineering, and scientific communities. His breakthrough occurred in two months and increased the life of a bulb from 13 hours to 560 hours.
9. Boeing 777—The 777 is a commercial aircraft designed by the largest airplane manufacturer in the world. Boeing spent $4 billion using a new design process centered on teaming and computer models.
10. Apollo Moon Landing—The Apollo moon landing was one of the most difficult and costly projects humanity has ever undertaken. The rockets were a major portion of the design effort. The development of the Saturn V rocket used only two prototype launches before manned flight, compared to 91 prototypes for the Atlas rocket.
11. House—The family home in America is easy to design, but it is a major investment. Modifying existing designs is the normal design approach.
12. Central Arizona Project—The CAP is a 336 mile aqueduct built from the Colorado river to the central Arizona cities of Phoenix and Tucson. It cost $4.7 billion and took more than 20 years to build.
13. Great Pyramid at Giza—One of the Seven Wonders of the Ancient World, the Great Pyramid is still admired for its engineering. It was built around 2575 B.C. and took 20 years and 50,000 laborers.