The Journal of NCOSE, Volume I, Number I, July-September 1994

UNDERSTANDING SYSTEMS ENGINEERING THROUGH CASE STUDIES

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Introduction

Technical products define modern civilization. The ability to create these products quickly, accurately, and cost-effectively is what makes corporations successful. There is a process for designing technical systems that is critical for corporations to correctly understand and use. This paper analyzes case studies to help understand the system design process.

Case Study Approach

While researching the system design process, it became necessary to develop a series of case studies of actual technical designs. Through the use of case studies we can create a bridge between systems theory [25], [55], [32], [37], [47], and actual design efforts. The design studies are grouped as illustrated in Figure 1.

This figure compares 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. The 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 cannot 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.

Each design was categorized by a score computed for each case study. The scores report composite scores of the constituent parts of each axis on the graph in Figure 1.1. Each constituent part is an ordinal ranking within the category. We recognize that ordinal rankings are not usually additive, however in this case we have adjusted the categories so that the answers all pass a reasonableness test. Extreme examples can be conjured up that will not fit these rankings, but this scale fits these specific case studies, although it is not an unassailable system.

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 of the product.

(5) Quantity to be built from the design and the expected sales price of the product.

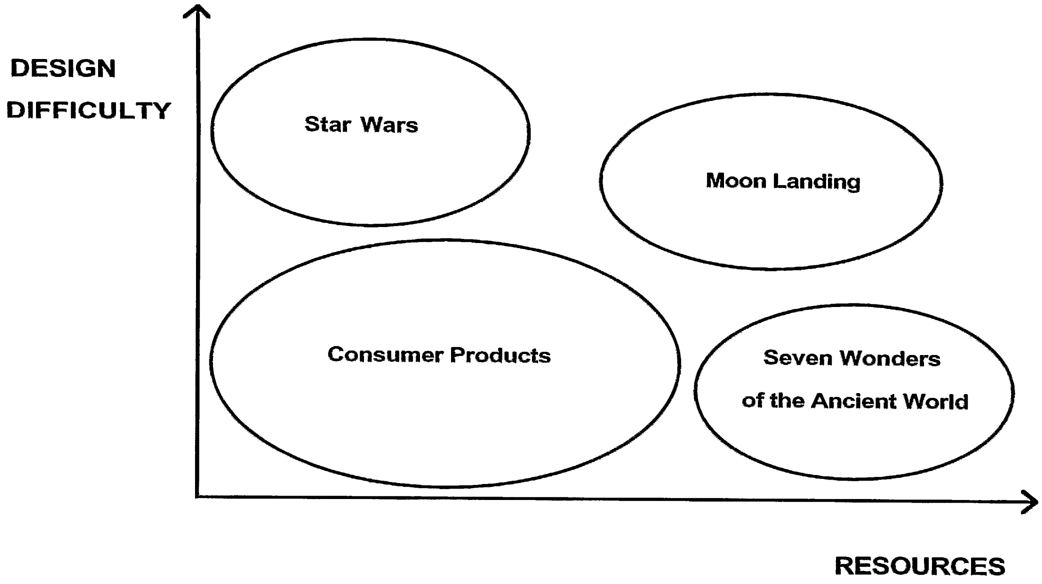

Figure 1 Categories of Design

Each case study was scored using the scale illustrated in Table 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 people embarking on a new design project.

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

Design type reflects whether feasible solutions exist, and how much original thought goes into the project. A score of 1-6 is awarded for continuous improvement. A score of 7-13 is given for original innovative design. A score of 14-15 is given for a breakthrough design effort.

Complexity of the knowledge needed to create the design is very hard to quantify. It is determined based on an estimate of the number and availability of the people with the necessary knowledge to do the design. A 1 or 2 is given for common knowledge held by many people, 3-5 for complex knowledge held by a sufficient pool of people, 6-8 for complex knowledge held by few people, and 9 or 10 for undiscovered knowledge that can only be found by specialists.

The number of steps needed to complete the design is defined as the number of discrete steps needed to design the system. It is related to the number of major components or major process steps that are needed to assemble the system. A 1 or 2 is assigned for any system with fewer than 50 steps or components. A 3 or 4 is assigned for systems up to 500 steps or components. A 5-8 is assigned for systems with more than 500 but less than 10,000 steps or components. And 9 or 10 is assigned for systems with greater than 10,000 steps or components.

Table 1 Design Difficulty Score

TYPE	KNOWLEDGE COMPLEXITY	STEPS	QUALITY	QUANTITY AND PRICE	DESIGN DIFFICULTY TOTAL
Range of 1-15	Range of 1-10	Range of 1-10	Range of 1-10	Range of 1-5	Range of 5-50

Quality is measured by how closely the final product must match the customer's specified target values. Customers provide a desired operating requirement. How well the system adheres to this requirement over its expected life is the quality measure. A score of 1-3 is given for little expectation of compliance. A score of 4-8 is for increasingly tight expectations, and a 5 is given for strict, unyielding expectations. It was very difficult to assign scores for this metric. that would satisfy all of the potential customers.

The quantity to be produced from the design is the production build number. By definition, the system design process ends with the creation of the first production unit. The number of systems built after the first unit is of interest to analyze the level of difficulty to create the manufacturing processes. If a large quantity of items must be built, more effort is exerted in designing the manufacturing system in addition to the product, thus yielding a more complex design problem.

The price of the final product is related to the build quantity, and becomes a design constraint. If there is a limit on the maximum selling price through market or other forces, then the design will be more difficult. A 1 is assigned for three or less units built, 2 for up to 100 units, 3 for up to 1,000 units, 4 for up to 5,000 units, and 5 is for greater than 5,000 units built. Perhaps Quantity and Price should have been two separate metrics, but often they are closely related, so we combined them.

The scores of the horizontal axis of the graph, 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.

(3) Infrastructure required to complete the design.

The score for each case study was on the scale illustrated in Table 2.

The Resources Axis.

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, it is easy for a rich man to afford a VAX computer, but not a person with an average salary. Combine 1,000 average salaries and these people can now afford a VAX. For the U.S. government a Cray computer has low cost, but for most people a 486 PC is expensive. A 1 or 2 is assigned for affordable systems, 3-8 for moderately expensive systems, 9-13 are for very expensive systems that are developed rarely, and 14 or 15 are for massively expensive systems requiring major sacrifices.

The time score is for time spent from the beginning of the effort to define the customer's needs through the first production unit. A 1 is given for less than 3 months, 2 for around 6 months, 3 for a year, 4-7 for up to 5 years, 8-9 for up to 8 years and a 10 for more than 8 years.

Table 2 Resources Scores

COST	TIME	INFRASTRUCTURE	RESOURCES TOTAL
Range of 1-15	Range of 1-10	Range of 1-10	Range of 3-35

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, the laws and legal protections, the skilled managers, and the educational system available. Infrastructure must be judged in regard to the designer's ability to get and use the infrastructure over the needed design time. A 1 or 2 is assigned if it is a common, low cost infrastructure (e.g. clean tap water in the U.S.). The numbers 3-5 are given for moderate infrastructures requiring people on the project to support it, 6-8 for large, complex infrastructures requiring large portions of the cost of the entire project, and 9 or 10 for a massive infrastructure requiring major portions of the available labor force and the available equipment.

All of the measures depend heavily on the context of the design effort. It is impossible for a man in a primitive country to obtain the resources necessary to build a telephone in a reasonable time. It is trivial to do this in America. It may be impossible for a small company to obtain $10 million to fund a new product. 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 reason for the scores.

Case Studies

In the following paragraphs we give a brief description of our 17 case studies. References and a fuller discussion are given in [24].

(1) Resistor Network - A serial or parallel combination of up to four resistors, designed to achieve a specific resistance value. Designing a resistor network is an NP-complete math problem, but is simple if only four resistors are used. [35].

(2) SIERRA Train Controllers - Students at the University of Arizona have developed numerous versions of a controller to run two toy trains. The controller must prevent collisions and can be accomplished with three to six state machine designs. Despite being limited to nine components, students have found dozens of successful solutions. [25].

(3) Bat Chooser - Bat Chooser is a small consumer product developed to determine the ideal bat weight for an individual baseball player. By measuring the swing speed of a given bat, the ideal weight of bat for the player can be selected. [22].

(4) Pinewood Derby - A Pinewood Derby is a Cub Scout race of wooden cars. Creating a round robin schedule format for 15 cars and 3 lanes proved to be an NP-complete math problem. Several bright engineers spent an inordinate amount of time chasing a problem with no solution. [25], [19].

(5) Second Opinion - An expert system that runs on a personal computer and provides an evaluation of childhood stuttering. It provides a second opinion to clinicians who are evaluating children. [20], [21].

(6) American Airlines Scheduling - American Airlines schedules its aircraft and crews using computer algorithms. These sophisticated algorithms search a fast solution, but not necessarily the optimum. [15], [31], [51], [16].

(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. [36], [12], [13], [8], [4], [41].

(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. [26].

(9) Boeing 777 - The 777 is a new commercial aircraft being designed by the largest airplane manufacturer in the world. Boeing is spending $4 billion and using a new design process, centered on teaming and computer models. [2], [1], [49], [18], [23].

(10) The Apollo Moon Landing - The Apollo moon landing was one of the most difficult and costly projects mankind 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 Mercury program's Atlas rocket. [39], [29], [44], [52].

(11) A House - The family home in America is easy to design, but it is a major investment. Modifying existing designs is the normal design approach. [38], [45].

(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. [17], [46], [43], [14].

(13) The 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 in 2575 B.C. and took 20 years and 50,000 laborers. [11], [40].

(14) A New Car - The redesign of new cars is one of the most costly ventures in modern industry. Japanese and American corporations do it differently. The Japanese spend on average 46 months, while the Americans take over 60 months. The difference can mainly be attributed to the Japanese use of rapidly developing prototypes. [53], [33], [34], [27].

(15) The GM Impact : An Electric Vehicle - The Impact is an electric vehicle designed with the sponsorship of General Motors. It has impressive specifications for a battery-operated car. [30], [10], [9], [28], [5], [54], [6], [7].

(16) Batteries for Electric Vehicles - Batteries are preventing the widespread use of electric vehicles. A breakthrough in energy storage is needed. This may not occur; instead, incremental design changes may eventually give a decent battery. [28], [42], [48], [54], [3].

(17) C3P0 - This handy robot in the Star Wars film is an intractable design problem for 1994 America. [50].

Table 3 and Table 4 show the summary scores for all of the case studies. Figure 2 plots all of the case studies together on one chart. Many, many more case studies can be extracted from the literature. We were trying to derive a minimal set that would be useful for systems engineers embarking on a new design project. We started by reading two or three books and numerous articles on each case study. Next, we condensed the system engineer's roles and the critical design requirements into a case study ranging from 3 to 10 pages in length. The scores for each study were derived from multiple discussions between the authors, students in graduate courses at the University of Arizona, and employees of Sandia National Laboratory.

Usefulness Of A System Design Metric

This system of rating system design efforts is valuable for several reasons. First, the best way to instruct engineers on the methods of system design is to use case studies. Design is as much an art as a science, and by studying how well other design efforts were done, lessons can be learned and applied to future projects. The evaluation scheme presented here is one method of showing what designs were successful given the resources available.

Table 3 Design Difficulty Scores For The Case Studies

Case Study	Type	Knowledge Complexity	Steps	Quality	Quantity and Price	Design Difficulty Total
Resistors	1	1	1	1	1	5
SIERRA	2	2	1	1	1	7
Bat Chooser	6	5	1	2	1	15
Pinewood	3	2	2	2	1	10
Second Opinion	5	6	3	3	3	20
American Airlines	5	4	4	2	2	17
Super Conductor	15	10	2	3	2	32
Light Bulb	14	6	3	2	4	29
777	9	6	9	7	3	34
Apollo	12	7	10	10	2	41
House	2	1	4	3	1	11
CAP	4	2	5	3	1	15
Pyramid	5	4	4	1	1	15
Car	7	4	6	3	5	25
Electric Vehicle	10	7	5	3	2	27
Improved Battery	8	6	3	2	4	23
Breakthrough Battery	15	9	3	3	5	35
C3P0	15	10	10	5	4	44

Table 4 Resources Scores For All Of The Case Studies

Case Study	Cost	Time	Infrastructure	Resources Total
Resistors	1	1	1	3
SIERRA	1.5	1	1	3.5
Bat Chooser	2	3	2	7
Pinewood	2	2	1.5	5.5
Second Opinion	2	6	3	11
American Airlines	3	5	5	13
Super Conductor	2	3	4	9
Light Bulb	3	3	2	8
777	13	7	8	28
Apollo	15	9	10	34
House	10	3	7	20
CAP	12	9	6	27
Pyramid	15	10	9	34
Car	9	7	6	22
Electric Vehicle	7	4	4	15
Improved Battery	3	10	4	17
Breakthrough Battery	5	6	5	16
C3P0	2	2	3	7

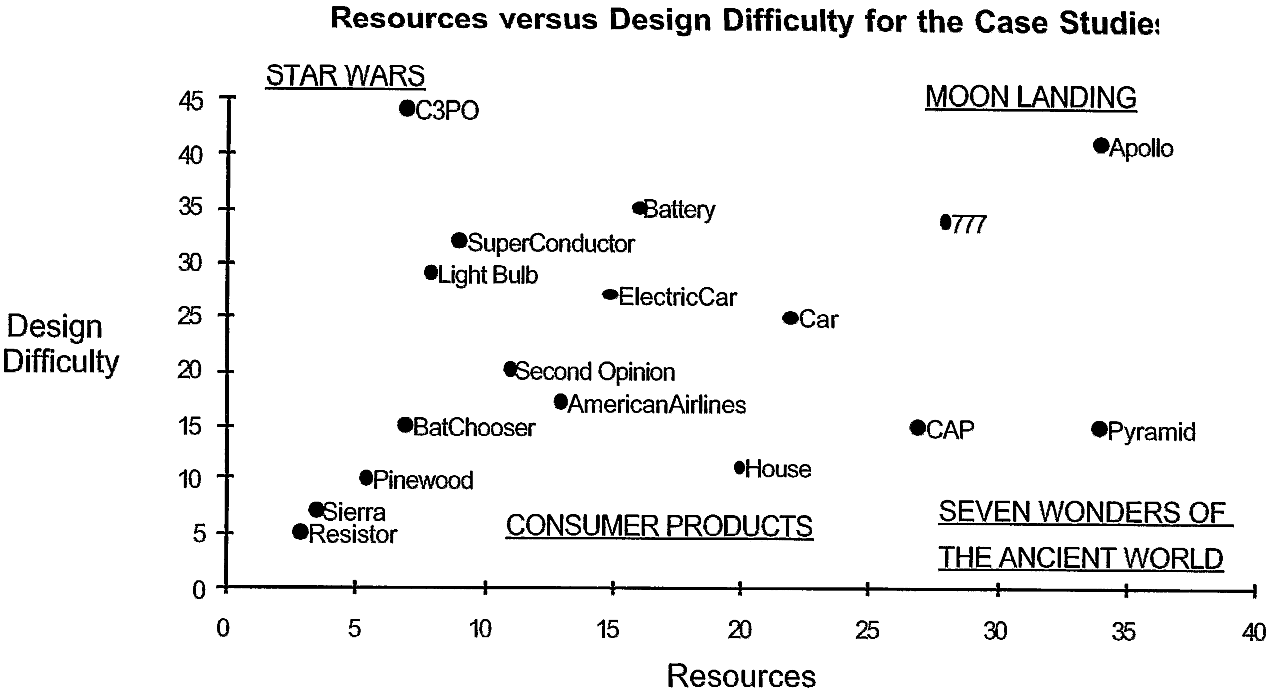

Figure 2 Actual Scores For The 17 Case Studies Plotted In Relationship To Each Other

The second, and main reason for such a system of measurement is to rate proposed design efforts before they even start. Corporations that must make a profit to survive must only attempt those projects in the Consumer Products region. Any design effort outside this region will require resources outside the scope of most ventures. Those ventures in the Star Wars arena are best left to academics and research labs, where lack of immediate success is not punished. If your customer asks you to build a system that fits into the Star Wars quadrant, you should tell them at the beginning that it cannot be done with the allotted resources. Those that are considered one of the Seven Wonders of the Ancient World are strictly for governments. Not only do these ventures not pay for themselves, but they also require despotic power to implement, since there is so little reward for the citizens involved. And finally, those in the Moon Landing area require government and industry involvement to succeed, since they require too large a share of the national resources.

We expect systems engineers to look at requirements for a new design, assemble an interdisciplinary team of customers, designers, manufacturing engineers, sales, product support, etc. and develop a consensus for the amount of resources required and the design difficulty. We believe that an analysis, such as that presented in this paper, would lead the system design team to decide the scope of the project and the appropriateness of the resources to the task. Additional effort is now being directed at using the case studies to decide when systems design requirements must be formally documented and when a full time systems engineer is needed for a design task.

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