EVALUATION IN SYSTEMS ENGINEERING

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Summary

Most of the projected life-cycle cost and the effectiveness of a given system, product, or structure is traceable to decisions made during the early stages of system design and development. These decisions pertain to performance and effectiveness factors, the design configuration, production quantity, utilization factors, maintenance concept, logistic support, and disposal plan.

Such decisions guide detail design and development activities, product distribution activities, and elements of sustaining system support. If the cost and effectiveness is to be satisfactory, it is essential that a high degree of analytical decision support emphasis be applied during system design and development in an integrated and iterative manner.

There are many technical and non-technical decisions and actions required throughout the system life cycle. Most actions, particularly those in the earlier phases, have life-cycle implications and greatly affect life-cycle cost and system effectiveness. Accordingly, Cost-Effectiveness Analysis should be employed in the evaluation of alternative system design configurations, alternative production schemes, alternative logistic support policies, alternative disposal concepts, etc.

This analysis process is iterative in nature and can be applied to any phase of the life cycle of the system, product, or structure.

Basic concepts inherent in Cost-Effectiveness Analysis are being applied to a broad range of applications in both the defense and the civilian sectors of public activities. More recently, CEA is finding a place in the design and development of systems for commercial sector applications worldwide.

In all applications, the joint consideration of life-cycle cost and effectiveness is an essential element in system design evaluation, and system design evaluation is essential during the process of bringing systems into being.

1. Introduction

Systems Engineering (SE) is a technologically based interdisciplinary process for bringing systems, products, and structures (human-made entities) into being. Human-made entities should be designed to satisfy human needs and/or objectives effectively, while minimizing system life-cycle cost as well as the intangible costs of ecological and societal impacts.

The evaluation of life support systems should begin during design and focus on the entire life cycle. It is essential that the designed entity be capable of serving in an environmentally friendly manner, with minimum impacts upon people. Accordingly, system cost, system effectiveness, and interactions between the natural world and the human-made world should be considered jointly, as is indicated in Figure 1.

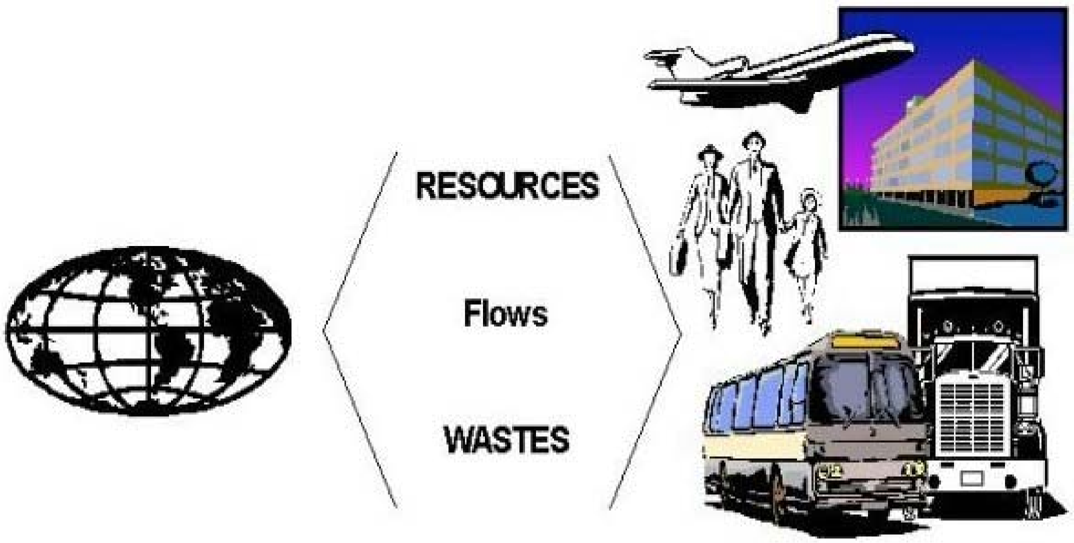

Figure 1: The Natural and the Human-Made World

Organization, humankind's most important innovation, is the time tested means for bringing human-made entities into being. While the main focus is nominally on the entities themselves, Systems Engineering embraces a better strategy.

SE concentrates on ***what the entities do*** before determining ***what the entities are***. That is, instead of offering systems or system elements and products per se, the organizational focus should shift to designing, delivering, and sustaining functionality, a capability, or a solution.

2. Integration and Iteration in System Design Evaluation

System design is the backbone of SE, with system design evaluation as is its compass. System design requires both integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation, as is shown generically in Figure 2.

It is essential that the technological activities of synthesis, analysis, and evaluation be integrated and applied iteratively over the system life cycle.

This follows from the observation that the commitment to technology, configuration, product performance, and cost is particularly acute during early stages of the system life cycle, as is illustrated in Figure 3.

The undesirable gap between commitment and system specific knowledge (A-A' and B-B') may be reduced by effective integration and adequate iteration as the design process evolves.

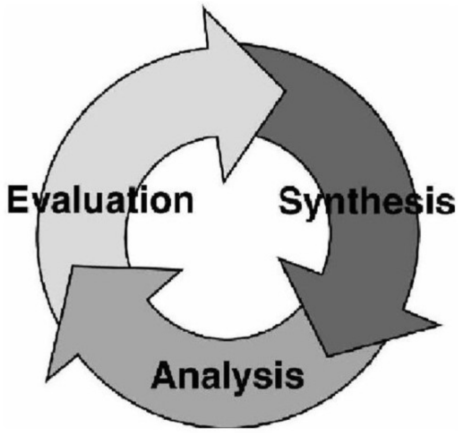

Figure 2: Synthesis, Analysis, & Evaluation

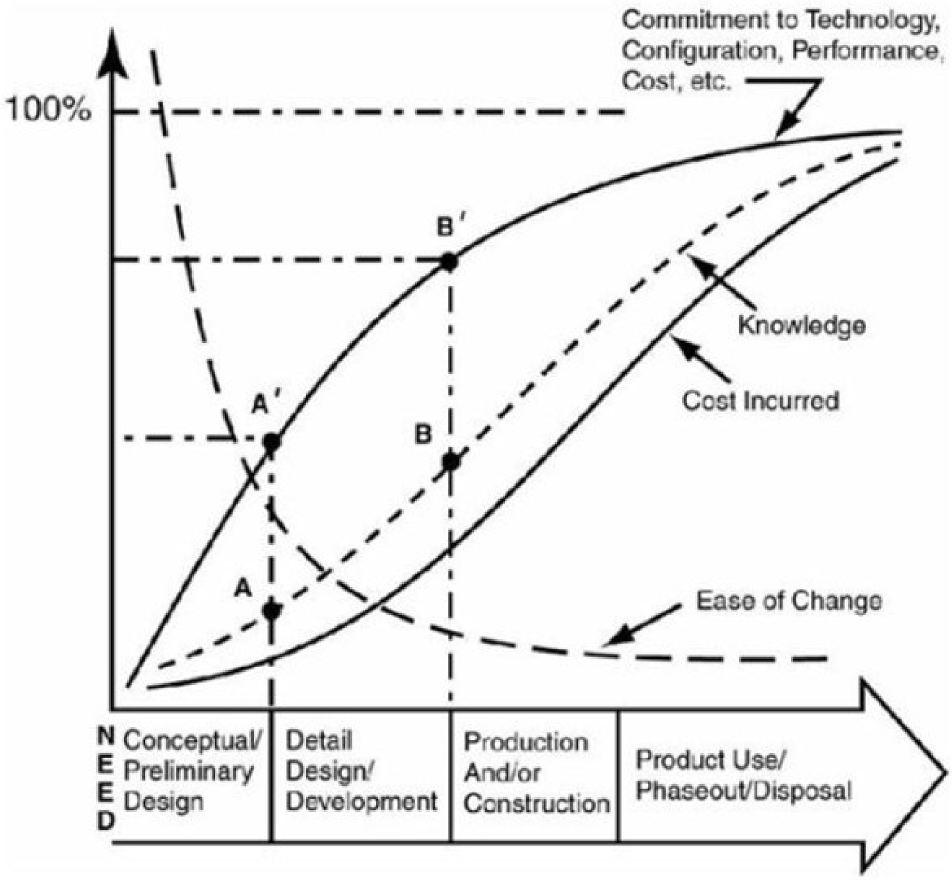

Figure 3: Commitment over the Life Cycle

2.1 A Morphology for Synthesis, Analysis, and Evaluation

Figure 4 presents a high level schematic of the system design process from a product realization perspective. It is a morphology for linking applied research and technology (Block 0) to customer needs (Blocks 1). It also provides a structure for the technological activities of synthesis, analysis, and evaluation. Each of these technological activities is summarized in the paragraphs that follow, with reference to relevant blocks within the morphology.

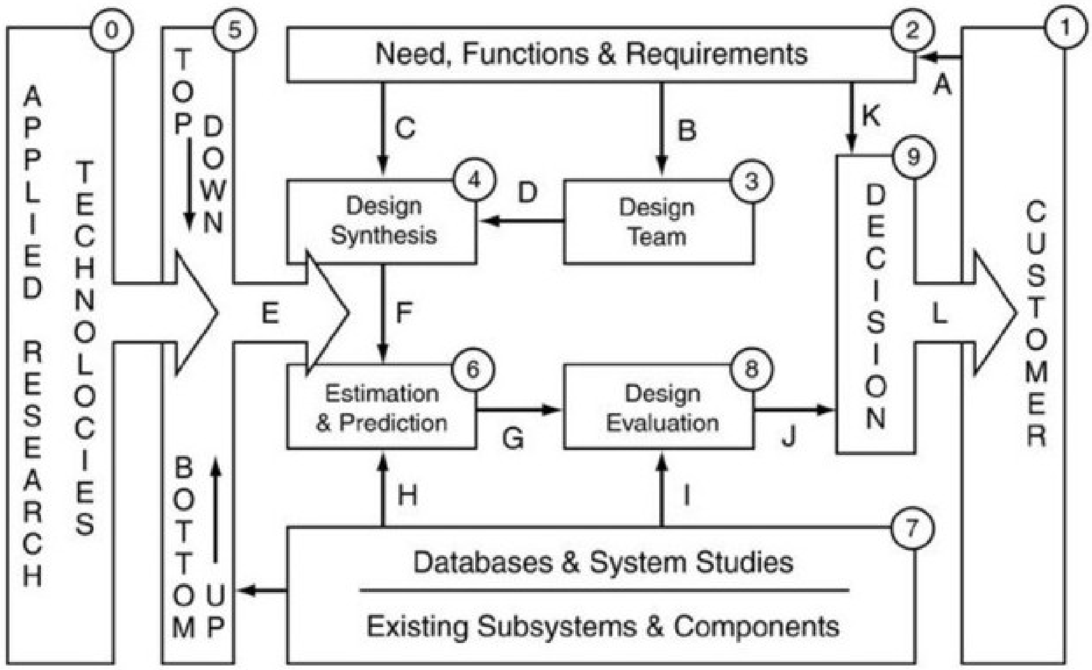

Figure 4: System Design Morphology for Product Realization

2.1.1 Synthesis

To design is to synthesize and project what might be, for a specific set of customer requirements, normally expressed in functional terms (Block 2). Synthesis is the creative process of putting known things together into new and more useful combinations. Meeting a need in accordance with customer requirements is the objective of design synthesis.

Primary elements enabling design synthesis are the design team (Block 3) supported by traditional and computer based tools for design synthesis (Block 4). Design synthesis is best accomplished by combining top-down and bottom-up activities (Block 5). Existing components, parts, and subsystems are then integrated to generate candidate designs for analysis and evaluation.

2.1.2 Analysis

Analysis of candidate system or product designs is a necessary but not sufficient ingredient in system design evaluation. It involves the functions of estimation and prediction of Design - Dependent Parameter (DDP) values (Block 6), the forecasting of Design - Independent Parameter (DIP) values from information found in physical and economic databases (Block 7). Systems analysis and operations research is a step on the way to product design evaluation, but adaptation of the models and techniques is required. The adaptation embraces customer requirements and invokes applied decision theory.

2.1.3 Evaluation

Each candidate design (or design iteration) should be evaluated against other candidates and checked for compliance with customer requirements. Evaluation of each candidate in Block 8 is accomplished after receiving DDP values for the candidate from Block 6. It is the specific values for DDP's that differentiate (or instance) candidate designs. DIP values derived in Block 7 are externalities. They apply across all candidate designs being presented for evaluation. Each candidate is optimized in Block 8 before being presented to the design decision schema (Block 9). It is here that the best candidate is sought. The choice is subjective and should be customer centered.

2.2 Discussion of the Ten Blocks

This section presents a discussion of the functions accomplished by each block in the system design morphology that was exhibited in Figure 4. The discussion will be at a greater level of detail than the description of synthesis, analysis, and evaluation given above.

2.2.1 The Technologies (Block 0)

Technologies are the product of applied research as indicated in Block 0. They evolve from the activities of engineering research and development and stand ready to be incorporated into candidate system designs. As a driving force, technologies are the most potent ingredient in the advancing capabilities of systems, products, and structures.

It is the responsibility of the designer/producer to propose and help the customer understand what might be for each technological choice. Those producers able to articulate and deliver appropriate technological solutions on time and within budget will usually attain and retain a competitive edge in the market.

2.2.2 The Customer (Block 1)

The purpose of system design is to satisfy customer (and stakeholder) needs and expectations. This must be with the full realization that the success of a particular design is ultimately determined by the customer in Block 1.

During the design process, all functions to be provided and all requirements to be satisfied should be determined from the perspective of the customer, or the customer's representative. Stakeholder and any other special interests must also be reflected in this "voice of the customer" in a way that reflects all needs and concerns. Included among these must be ecological and human impacts. Arrow A represents the elicitation of customer needs and requirements.

2.2.3 Need, Functions, and Requirements (Block 2)

The purpose of this block is to specify the behavior of the product or system in functional terms. A market study identifies a need, an opportunity, or a deficiency. From the need comes a definition of the basic requirements in functional terms. Requirements are the input for design and operational criteria and criteria are the basis for evaluating candidate product configurations.

At this point, the product or system should be defined by its function, not its form. Arrow A indicates customer inputs that define need, functionality, and operational requirements. Arrows B and C depict the transfer of this information to the design process.

2.2.4 The Design Team (Block 3)

The design team should be organized to incorporate in-depth technical expertise, as well as a broader systems view. Included must be expertise in each of the product life-cycle phases and elements contained within the set of system requirements.

Balanced consideration should be present for each phase of the design. Included herein would be the satisfaction of intended purpose, followed by producibility, reliability, maintainability, disposability, environmental compliance, and others. Arrow B depicts product requirements being imposed on the design team and Arrow D the teams contributed effort to synthesis where need, functions, and requirements are again the overarching consideration (Arrow C).

2.2.5 Design Synthesis (Block 4)

To design is to project what might be. Design synthesis is a creative activity that relies on the knowledge of experts about the state of the art as well as the state of technology. From this knowledge, a number of feasible design alternatives are fashioned and presented for analysis. Depending upon the phase of the product life cycle, the synthesis can be in conceptual, preliminary, or detailed form. Design team members must be willing to question their own conclusions about a design, so as to go beyond preconceived notions.

The candidate design is driven by both a top down functional decomposition and a bottom up combinatorial approach based on available elements. Arrow E represents a blending of these approaches. Adequate definition of each design alternative must result to allow for life-cycle analysis in view of the requirements. Arrow F highlights this definition process as it pertains to the passing of candidate design alternatives to design analysis in Block 6.

Alternatives should be proposed for analysis even though there seems to be little likelihood that they will prove to be feasible. This should be with the thought that it is better to consider many alternatives than to overlook one that may be very good. Alternatives not considered cannot be adopted, no matter how desirable they may actually have proven to be.

2.2.6 Top Down & Bottom Up (Block 5)

Traditional engineering design methodology is based on a bottom-up approach. Starting with a set of defined elements, designers synthesize the product by finding the most appropriate combination of elements. The bottom-up process is iterative with the number of iterations determined by the skill and creativity of the design team as well as by the complexity of the product. A top-down approach to design is invoked by SE. Starting with requirements about the external behavior of any part of the system (in terms of the function provided by that part), that behavior is then decomposed. These decomposed functional behaviors are then described in more detail and made specific through an analysis process. Then, the appropriateness of this choice of functional components is verified by synthesizing the original entity. Most products are realized through a combination of the top-down and bottom-up approaches, with the best mix being largely a matter of experience. Arrow F represents the output candidate designs ready for analysis.

2.2.7 Estimation and Prediction (Block 6)

During estimation and prediction, cost and effectiveness measures are generated using models and database information to estimate and predict Design-Dependent Parameter (DDP) values for each design alternative (Block 6). These models and simulations are based on assumptions, physical laws, and empirical data. The DDP values provide the basis for comparing system designs against input criteria to determine the relative merit of each alternative. Arrow H represents input from the available databases and from relevant studies.

2.2.8 Physical and Economic Databases (Block 7)

There exists a body of knowledge that engineers, economists, and technologists rely on to perform analysis and evaluation tasks. This body consists of known physical laws, empirical data, price information, economic forecasts, and other studies and models.

Block 7 represents a resource for the design process, rather than being an actual step in the process flow. It is here that Design - Independent Parameter values are determined and provided to design evaluation, as is represented by Arrow I. Block 7 also includes descriptions of existing system components, parts, and subsystems. It is important to use existing databases in doing analysis and synthesis to avoid duplication of effort. This body of knowledge and experience can be utilized both formally and informally in performing needed studies and in supporting the decisions that follow

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Biographical Sketch

Wolter J. Fabrycky is Chairman of Academic Applications International, Inc. He is also the Lawrence Professor Emeritus of Industrial and Systems Engineering at Virginia Tech and a Registered Professional Engineer in both Arkansas and Virginia.

Wolt Fabrycky received the Ph.D. in Engineering in 1962 from Oklahoma State University, the M.S. in Industrial Engineering in 1958 from the University of Arkansas, and the B.S. in Industrial Engineering in 1957 from Wichita State University. Dr. Fabrycky taught at Arkansas and Oklahoma State and then joined Virginia Tech in 1965 where he served as Founding Chairman of Systems Engineering, Associate Dean of Engineering, and then as Dean of Research for the University.

Fabrycky received the Hotlzman Distinguished Educator Award from the Institute of Industrial Engineers in 1990, the Grant Award in 1994, and the Wellington Award in 2004. He received the Lohmann Medal from the College of Engineering at Oklahoma State in 1992 for Outstanding Contributions to Industrial and Systems Engineering Education, Research, and Publications. Dr. Fabrycky is listed in Who's Who in Engineering and Who's Who in America.

Dr. Fabrycky was elected to the rank of Fellow in the Institute of Industrial Engineers in 1978, the rank of Fellow in American Association for the Advancement of Science in 1980, and the rank of Fellow in the International Council on Systems Engineering in 1999. Fabrycky received INCOSE's Pioneer Award in 2000 with the following citation: "An esteemed practitioner, teacher, and advocate of Systems Engineering. His service, as a collaborator with Ben Blanchard, allowed them to articulate the principles and objectives of Systems Engineering in a manner that conveys the tremendous potential and value added by this discipline".

Six Prentice Hall books were co-authored by Fabrycky. There are: Systems Engineering and Analysis (2006), Engineering Economy (2001), Economic Decision Analysis (1998), Life-Cycle Cost and Economic Analysis (1991), Procurement and Inventory Systems Analysis (1987), and Applied Operations Research and Management Science (1984). He also co-edits, with Joe Mize, the Prentice Hall International Series in Industrial and Systems Engineering that now contains more than 50 titles.