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Engineering Economy at the System Level

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Because of the intricacy required to explain the desirability of incorporating Engineering Economy at the system level, it seemed best to bifurcate the integrator and the integrated, presenting relevant material topic-by-topic. Instead of explaining each topic in its integrated form with concurrent justification, integration is made visible as though considered appropriate. Justification is provided within a text box at the end of each topic where it is offered for examination and critique.

Communicating from the general to the specific, is necessary in this paper. The system level will be recognized and addressed first, without getting overly enthusiastic about the potential for Engineering Economy (EE) when integrated at that level. Specifics will emerge from seven topics wherein Engineering Economy and the system level are shown to interface in a significant way. Specifics about these interfaces are addressed by EE@SL comments provided in each text box.

I. Recognizing and Addressing the System Level

The purpose of this paper may be realized most directly by recognizing the system of interest to be *the world in which we live*. We observe the *natural*, the *human-made*, and the *human-modified* worlds to be interconnected sectors as illustrated in Figure 1. Of these, it is the human-modified world that should be adopted as the highest-level system of concern. This section is devoted to describing EE@SL and considering academic subjects that have become most useful in enabling Engineering Economy to evaluate system design alternatives at that level.

The world in which we live. The *natural world* came into being by natural processes. The *human-made world* is made up of systems and products that resulted from the intervention of humans through components, attributes, and relationships. The *human-modified world* is the natural world into which the human-made has been introduced as systems, subsystems, entities, and artifacts; a world becoming increasingly complex. This paper strives to justify the human-modified world as the ultimate system level at which the viability of all that is human-made should be judged.

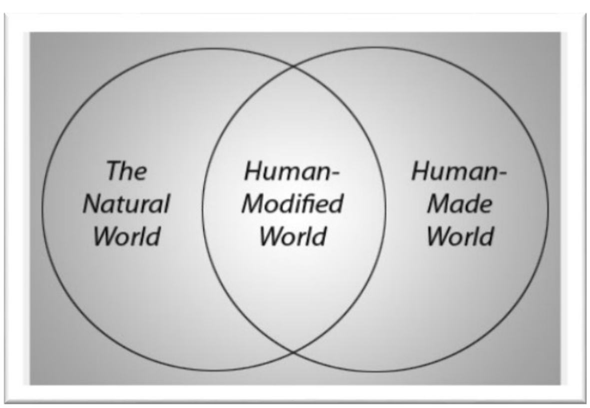

Figure 1. Our world as interconnected sectors

When brought into being, all that is human-made are embedded into the natural world. Important interfaces exist between human-made systems and natural systems. Each affects the other in many ways. The effect of human-made systems on the natural world has only recently become a keen subject for consideration by concerned people, especially when the effect is deemed undesirable.

Only recently have significant and complex human-made systems appeared. These systems make up the human-made world, their chief engineer being human. The rapid appearance of human beings is not adequately understood, but human presence has significantly affected the natural world, too often in undesirable ways. Primitive beings had little impact on the natural world, for they had not yet developed pervasive and potent enabling technologies.

Systemology and synthesis. The science of systems or their formation is called *systemology*. Problems and problem complexities faced by humankind do not organize themselves along disciplinary lines. New arrangements of scientific and professional efforts based on the common attributes and characteristics of needs and problems should contribute to progress. More attention should be paid to human action and praxeology applications at the macro-level to help understand both the economic and non-economic dimensions of the world in which we live.[1,12]

The formation of interdisciplines began in the middle of the last century and that has brought about an evolutionary synthesis of knowledge. This has occurred not only within science, but between science and technology and between science and the humanities. The forward progress of systemology in the study of large-scale complex systems requires a synthesis of science and the humanities in addition to a synthesis of science and technology.

When synthesizing human-made systems, unintended effects can be minimized and the natural system can sometimes be improved by engineering the larger human-modified system instead of engineering only the human-made. If system evaluation is applied beyond the human-made, then the boundary of the target system (meant to include both natural and human-made systems) should be adopted as the boundary of the human-modified domain.

Systems engineering. From its modest beginnings more than a half-century ago, systems engineering (SE) is emerging as an effective technologically based interdisciplinary process for bringing systems and services into being.[7] While the primary focus is nominally on the entities themselves, systems engineering is inherently oriented to considering "the end before the beginning". It concentrates on *what the entities are intended to do* before determining *what the entities are,* with form following function.

Systems engineering is concerned with the *engineering* of human-made systems and with systems analysis. In the first case, emphasis is on the process of bringing systems into being, beginning with the identification of a need or deficiency and extending through requirements determination, functional analysis and allocation, design synthesis and evaluation, design validation, deployment and distribution, operation and support, sustainment, and phase-out and disposal. In the second case, focus is on the improvement of systems already in being. By utilizing the iterative process of analysis, evaluation, modification, and feedback, most systems now in existence can be improved in their operational effectiveness, delivered service quality, user affordability, product and environmental sustainability, and stakeholder satisfaction.

The systems approach is increasingly being considered by forward-looking private and public organizations and enterprises. It is applicable to most types of systems, encompassing the human activity domains of communication, defense, education, healthcare, manufacturing, transportation, and others named in the National Academy of Engineering compilation of Grand Challenges.[10]

Operations research and management science. Operations research (OR) and the management sciences (MS), provide a body of systematic knowledge embracing models, modeling, and simulation approaches for preforming systems analysis (SA).[4,9] Applicable to operations and management as the name implies, OR/MS has been found to be necessary but not sufficient for Engineering Economy to be rigorously linked to operations. Accordingly, both OR and MS will be recognized in the sections that follow as primary enablers for EE@SL to provide more opportunities to "think about the end before the beginning".

EE@SL Section I: Establishing the WHAT and the WHY and addressing the HOW

- **The WHAT is the human-modified world. The WHY is because that is the only world in which we are privileged to live.**
- **Although the human-modified world is easy to recognize, the HOW is not easily realized. Some steps toward realization are offered in this paper by recommending seven initiatives listed below:**
  1) **An expanded version of cost / benefit / effectiveness analysis should be invoked with the human - modified world as the focus, beyond what an ordinary objective function includes (Section I).**
  2) **Expanding and rethinking capital investment for early system life-cycle decisions, intended to recognize and capture the benefit of commitment minimization over the life cycle (Section II).**
  3) **Integrating and iterating synthesis, analysis, and evaluation concurrently, with Engineering Economy seeking out and engaging where and whenever synthesis is taking place (Section III).**
  4) **Accepting system parameters and the design dependent parameter paradigm as the mechanism for linking operational outcomes with design causes early in the system life cycle (Section IV).**
  5) **Use life-cycle economic models for evaluation that incorporate DDP's and an expanded concept of equivalence including OR and MS (within SE) for linking EE to the system level - Section V.**
  6) **Seek the preferred system design alternative in the face of applicable constraints and requirements wherein subjective judgement is given the position of prominence (Section VI).**
  7) **Identify system design examples with generic characteristics that may be used to leverage the utilization of Engineering Economy at the system level, EE@SL (e.g., REPS - Section VII).**
- **Engineering Economy as currently taught and practiced is judged to be inadequate for the system-level involvement promulgated in this paper. Advancing EE@SL would be significantly enabled by:**
  1) **Economic Theory, suggested to be as in *Human Action.*[12] Start with a no cost subscription through the von Mises Institute, articles@mesis.org.**
  2) **Organization Theory, humankind's most important innovation, suggested to be as in *The Functions of the Executive.*[1] Become acquainted with this human-action based approach promulgated by Holger Thuesen beginning in the 1950's and subsequently by Paul Torgersen since about 1962.**
  3) **Systems Thinking, suggested to be as in *Systems Engineering and Analysis.*[2,6] Consult this 5th Edition Pearson book and access the no cost supporting materials offered on www.a2i2.com.**
  4) **Finally, note that the general theme and objectives of this paper are being promulgated by the international honor society for systems engineering, showcased on www.omegalpha.org.**

II. Extending Capital Investment Decision Making

Without a doubt, capital investment analysis (capital budgeting) is the most pervasive activity upon which Engineering Economy is promulgated.[3] But as the next section will demonstrate, system synthesis, more than analysis, is often the process whereby goods (particularly producer and public goods) are acquired. And in the case of complex systems, there may be no choice but to acquire the needed capability through capital investment that invokes system design and development.

With EE@SL, there will likely be consideration of a life cycle with an acquisition phase involving more than simple procurement choices. Years are sometimes involved in bringing the complex systems and services of today into being. The enterprise may have to reckon with an extended phase of the acquisition cycle. In those instances where acquisition is simply by commercial off-the-shelf (COTS) purchasing, the notion of an acquisition phase remains applicable, albeit with a shorted time duration. Classical capital budgeting methods are not quite adequate to address the human-modified world if employed in classical mode alone.

Commitment considerations in system design. The systems engineering process is applicable over all phases of the life cycle, with the greatest benefit being derived from its utilization in the early phases as shown in Figure 2. Great benefit can be derived from accelerating the accumulation of system specific knowledge early in the system life cycle. Fully two-thirds of the commitment to final system characteristics, life-cycle cost, environmental impact, and sustainability are made by the time conceptual and preliminary system design concludes, as is implied in Figure 2.

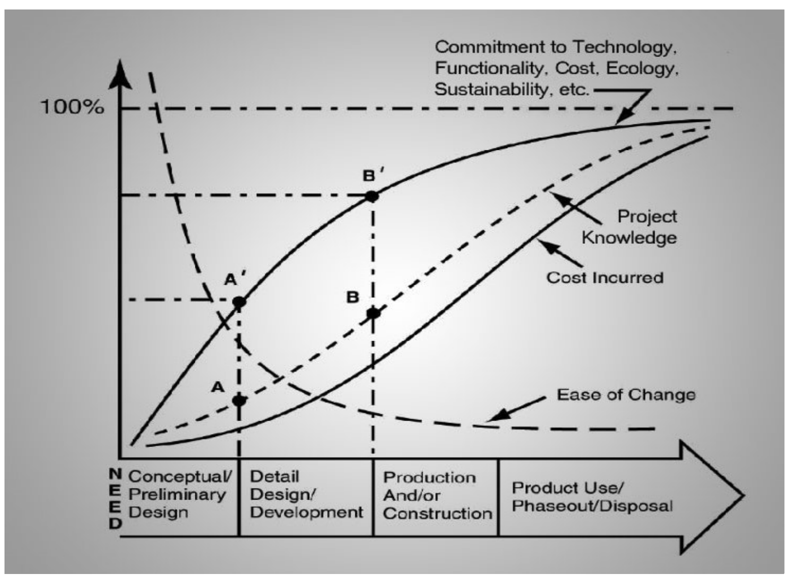

Figure 2. Commitment v/s phases of the system life cycle

There is usually a large commitment in terms of technology applications, the establishment of a system configuration and its performance characteristics, the obligation of resources, and potential life-cycle cost at the early stages of a program. It is at this point when system-specific knowledge is limited, but when major decisions are reached pertaining to the selection of technologies, the selection of materials and potential sources of supply, equipment packaging methods, and levels of diagnostics, the selection of manufacturing process, the establishment of a maintenance approach, and strategies for dealing with interface concerns with the natural world.

It is essential that the technological activities of synthesis, analysis, and evaluation be integrated and applied iteratively over the system life cycle. The objective is to influence design early, in an effective and efficient manner, through a comprehensive needs analysis, requirements definition, functional analysis and allocation activity, and then to address the follow-on activities in a logical and progressive manner, including the provision of feedback.

The overall objective is to influence design in the early phases of system acquisition, leading to the identification of classical discipline-based design needs. These should be applied in a timely manner as design evolves from system-level requirements to design of various subsystems and below. This follows from the observation that the commitment to technology, configuration, product performance, the environment, and cost is Pareto in nature.

It is during the acquisition stage (investment) where the implementation of systems engineering concepts and principles is critical. It is essential that one start off with an understanding of the customer need along with a good definition of system requirements. EE@SL has an important role to play, especially with regard to the economic dimensions of system design alternatives.

EE@SL: Section II – Capital investment during system design

- **Two deficiencies have been identified in considering the most useful engagement of EE@SL.**
  1) **Traditional engineering design focuses mainly on the acquisition phase of the system life cycle, with too little attention given to commitments that affect outcomes during operation.**
  2) **Traditional capital budgeting does not fully accommodate evolving mutually exclusive design alternatives as capital investment opportunities incorporating design optimization.**

- **Powerful approaches utilizing modeling and indirect experimentation (simulation) may be used to help narrow the undesirable gap between commitment and system specific knowledge within EE@SL. During design synthesis, A-A' and B-B' may be reduced by effective integration and adequate iteration as the system design process evolves. Capital budgeting misses this opportunity.**

Experience indicates that a properly coordinated and functioning system and its product, that is competitive in the marketplace, cannot be achieved through efforts applied largely after it comes into being. Accordingly, it is essential that design synthesis include operational considerations during the early stages of system design and development.

Legions of academicians and practicing professionals are developing and applying powerful tools for analysis, experimentation, modeling, simulation, animation, etc. to the domain of operations. These individuals represent the fields of industrial engineering, engineering management, operations research, management science, systems management, engineering economy, and others.

Too often the well-intended efforts of these individuals are ineffective because of being applied too late in the life cycle. These important domains and professional fields are necessary but not sufficient to put the human-modified world on the path of continuous improvement, as is greatly desired.

III. Integrating Synthesis, Analysis, and Evaluation

Instead of offering systems or system elements per se, organizations and enterprises are increasingly finding that systems engineering properly utilized facilitates the discovery of emergent properties to provide for the needs of people. An integration of process (synthesis) and analysis (to support evaluation) is shown in Figure 3 invoking the iteration of synthesis, analysis, and evaluation over the system life cycle.

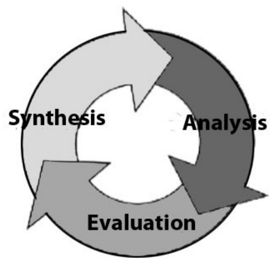

Figure 3. Iterating synthesis, analysis, and evaluation

Figure 4 provides a high-level schematic of the systems engineering process from a product realization perspective. It is a morphology for linking applied research and the technologies (Block 0) to customer needs and stakeholder interests (Block 1). It also provides a structure for visualizing the technological activities of synthesis, analysis, and evaluation. Each of these activities is summarized in the following paragraphs, with reference to relevant blocks within the morphology. It is essential that the technological activities of synthesis, analysis, and evaluation of Figure 2 be integrated and applied iteratively and continuously, guided by these 10 blocks.

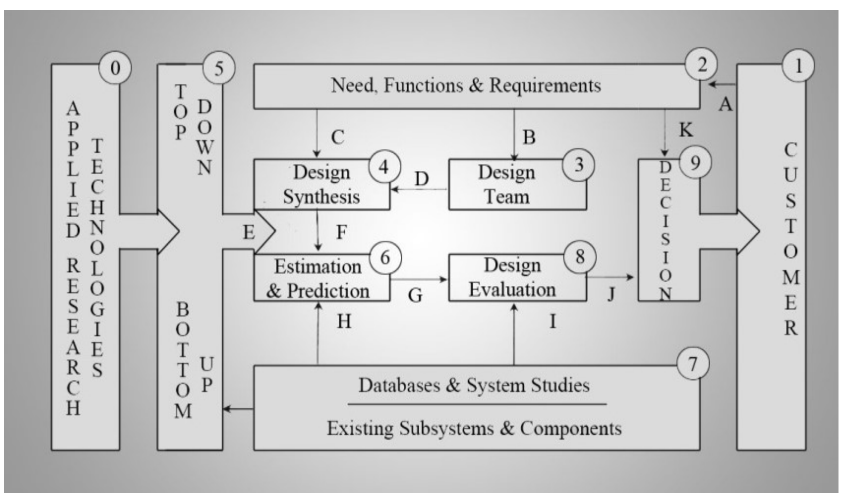

Figure 4. A morphology for systems engineering

Synthesis. To design is to synthesize, project, and propose what might be for a specific set of customer and stakeholder requirements, often expressed in functional terms (Block 2). Synthesis is the creative process of putting known things and newly developed entities together into more useful and new combinations to produce emergent properties. Meeting a need in compliance with customer and stakeholder requirements is the objective of design synthesis.

The 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 approaches (Block 5). Existing and newly developed components, parts, and subsystems are integrated to generate candidate system designs for analysis and evaluation.

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 values (Block 6) and the forecasting of design-independent parameter values from information contained in physical and economic databases (Block 7).

Engineering Economy provides an essential and significant contribution to system design evaluation, but adaptation of the models and techniques to the domain of design is required. The adaptation must explicitly recognize and incorporate the mandate of customer requirements.

Evaluation. Each candidate design (or design alternative) should be evaluated against other candidates and checked for compliance with all customer and stakeholder interests. Evaluation of each candidate in Block 8 is accomplished after receiving parameter values for the candidate from Block 6. It is the specific values for parameters that differentiate (or instance) candidate system designs from each other.

Design-independent parameter values determined in Block 6 are externalities. They apply across all designs being presented. Each candidate is made equivalent in Block 8 before being presented to the customer for design decision. (Block 9). It is in Block 9 that the best candidate is sought. The preferred choice is subjective and should be made by the customer.

System Design Decisions. Block 9. Given the variety of customer needs and perceptions as collected in Block 2, choosing a preferred alternative is not just the simple task of picking the least expensive design. Input criteria, derived from customer and product requirements, are represented by Arrow K and by the design dependent values and life-cycle costs indicated by Arrow J.

The customer or decision maker must now trade off life-cycle cost against benefits and effectiveness criteria subjectively. The result is the identification of one or more preferred alternatives that can be used to take the design process to the next level of detail. Alternatives must ultimately be judged subjectively by the customer. Accordingly, Arrow L depicts the passing of evaluated candidate designs to the customer as well as stakeholders for review and decision.

Alternatives that are found to be unacceptable in performance terms can be either discarded or reworked with new alternatives sought. Alternatives that meet all, or the most important, functional criteria can then be evaluated based on estimations and predictions. This should be accompanied by risk assessment, another capability of Engineering Economy.

Engineering practice requires systems thinking more than ever before. Instead of offering systems or system elements per se, Engineering Economy properly linked through systems engineering in this new century should facilitate the discovery of emergent system properties that provide desired *functionality, capability,* and *improved operations.*[2,6]

In Reference 5, systems analysis (SA) is argued to be necessary but not sufficient for the teaching and practice of SE. The system design (or synthesis) process leads and usually sets the pace. Stumbling through the system design space requires an evaluation ‘compass’ to help converge system design in the face of multiple criteria. It is here that Engineering Economy can be at its best. Value for the customer relies on converging the design to achieve the desired outcome, hopefully “Quicker, Better, Cheaper” as sometimes informally stated.

Within the context of synthesis, analysis, and evaluation is the opportunity to implement systems engineering over the life cycle in measured ways that can help ensure its effectiveness in modifying the human-made world in which we live. It is a morphology for linking applied research and technologies (Block 0) to customer needs (Block 1). It also provides a formal structure for visualizing relationships among the technological activities of synthesis, analysis, and evaluation.

System design requires integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation over the system life cycle. Analysis acting alone is not sufficient for the evolution of synthesized system designs. Accordingly, Engineering Economy should be enabled at the system level to serve system design evaluation involving the entire design cycle.

EE@SL Section III: Go where synthesis precedes analysis and evaluation

Engineering Economy applied at the system level is essential. At that level, EE serves as a guide to synthesis. It can serve in the role of a ‘compass’ to help converge system design to economic and non-economic requirements for meeting the needs of humankind.

The human-made and human-modified worlds require integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation over the system life cycle.

Analysis acting alone is not sufficient for the evolution of synthesized system designs. Accordingly, Engineering Economy should be enabled at the system level to serve system design evaluation over the entire design cycle.

Synthesis must be embedded from the beginning. Analysis and evaluation are necessary to measure the anticipated synthesized result. It is synthesis that brings forth desired emergent properties. And it is emergent properties that are the evidence of engineering talent at work. Without synthesis, emergent properties would remain dormant awaiting discovery.

System design is the prime mover for systems engineering, with system design evaluation being its compass. The ‘compass’ too often concentrates largely on economic, factors. But if economic alone, impacts on the natural world may not be accommodated. Thus the importance of a compass that explicitly incorporates noneconomic criteria. EE@SL would remain impotent if it does not incorporate noneconomic criteria concurrently.

EE@SL as evaluator - Engineering Economy, properly integrated and focused on iteration, provides valuable guidance to guide the convergence of synthesis. EE is primarily analysis and evaluation oriented, with little synthesis. But it is right there that it must be linked to guide the synthesis process!

IV. The Design Dependent Parameter Paradigm

Figure 5 (left side) depicts the evolution of decision evaluation capability for operations. Begin with operations and focus on the scientific management thereof. Operations are continuously being researched (OR) and an extensive body of systematic knowledge has accumulated, herein called Management Science (MS). MS properly utilized enables the practice of Scientific Management (SM) of the operations researched. This is a knowledge generation, knowledge accumulation, knowledge utilization process for enterprise operations that originated more than a century ago.

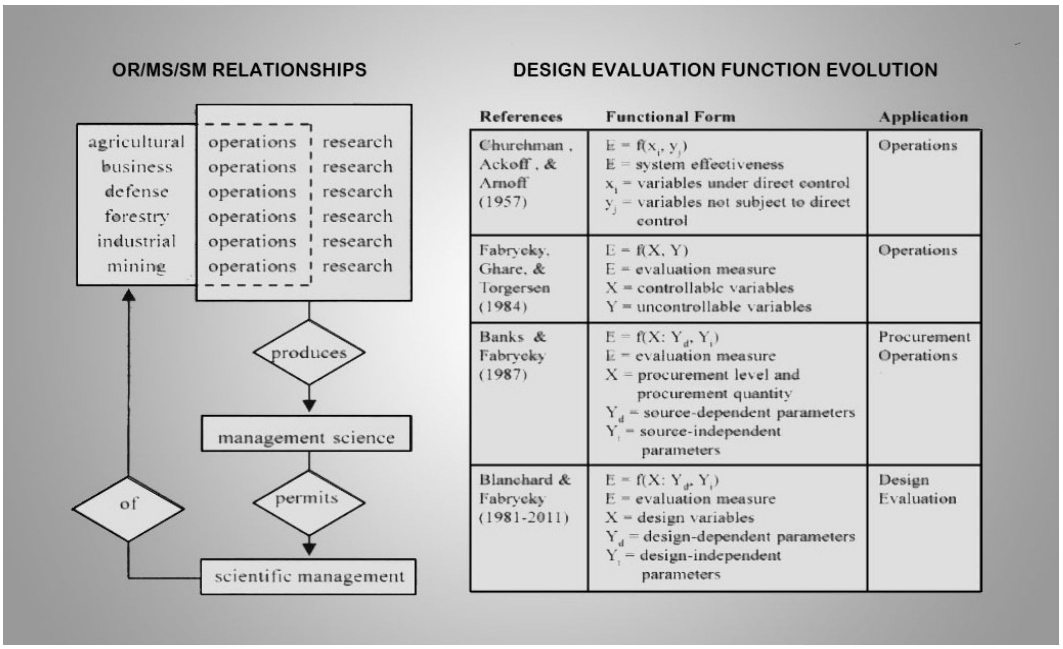

Figure 5. Evolution of the design evaluation function

Now consider the right side of Figure 5 depicting the application of analysis within design and operations. The first two entries are decision model formulations applicable to operations in general, specifically for systems analysis. The third entry is explicitly for procurement and inventory operations with recognition of source dependent parameters, enabling the quantification of source selection decisions. Herein lies the evolved mathematical basis and decision model background for the decision (design) dependent parameter paradigm (see the text box for more about entry three that goes back to your author's dissertation on the multisource item).

Design Dependent Parameters (DDP's) began to appear in the fourth entry of Figure 5 (right). These are well known parameters (producibility, reliability, maintainability, supportability, sustainability, disposability, and others) that make possible the evaluation of synthesized system designs, beyond function alone. Design dependent parameters values are manifested during operations, but have their characteristics determined during system design and development.

The DDP paradigm may now be traced (only weakly) to the classic *Introduction to Operations Research,* by Churchman, Ackoff, and Arnoff, 1957.[4] In the next year and with that OR book, it was your author's good fortune to study the subject when a MS student at Arkansas. But neither the authors of that classic book, the professor, nor yours truly could perceive what the generic mathematical construct stated in Chapter 1 could become for Engineering Economy and the unknown field of systems engineering. The mathematical construct referenced in this classic was $E = f(x_i, y_j)$, with the explanation that it was the general form of OR models. Churchman, et al stated that E represents the effectiveness of the system under study, x_i the variables of the system which are subject to control, and y_j those 'variables' (implying parameters) not subject to control.

That was all of it! The construct did not appear anywhere else in the book. Nor was it explained as the basic mathematical form behind specific categories of OR models. Also, design variables and design dependent parameters of reliability, maintainability, producibility, sustainability, and others were not recognized or even mentioned. Further, an index search of recent OR books by yours truly failed to reveal citations that would embrace DDP's, much less parameters in general.

EE@SL Section IV: Inspiration from Decision Dependent Parameters

Unknowingly at the time, your author did not see the power of parameters to augment the capability of discriminating among mutually exclusive alternatives. The year was 1962 and my dissertation was up for defense. Optimal Inventory Policy for the Multisource Item was the research topic. <u>How much</u> and <u>when</u> were extended to include embrace answers to <u>from what source</u>. Key to source selection was recognition of source dependent parameters. This and follow-on research was extended, summarized, and published (Prentice Hall, 1987 as cited in Figure 5), but even by then parameters had not been generalized to include mutually exclusive design alternatives,

- ❖ **With the publication of *Applied Operations Research and Management Science* by Fabrycky, Ghare, and Torgersen (Prentice Hall, 1984) a comprehensive mapping of Churchman, et. al. on most of the categories of OR/MS models became available.[9] Although limited to the domain of operations, this textbook made explicit the role of parameters as controllables for application in evaluating alternatives.**

- ❖ **AORMS focuses exclusively on the improvement of operations, mostly through optimization.[9] The domain of system design with design dependent parameters still had not been recognized. Engineering Economy is capable and the most appropriate subject to employ DDP's to bring its prowess to the system level. Money flow modeling, mapped over the complete life cycle, is the key to linking system design with operational outcomes experienced in the human-modified world.**

- ❖ **DDP's are controllable along with design variables during the process of bringing systems and products (human-made entities) into being. DDP's are partitioned from Design Independent Parameters (DIP's - externalities not controllable during design). This focus is most effective when based on design for the product life cycle, recognizing the concurrent factors of production, support, phase-out, and disposal that are illustrated conceptually in Figure 6 of the next Section.**

- ❖ **Each domain of engineering has its own customized analysis methodology for evaluation, and that is necessary. But this paper emphasizes the importance of Design Dependent Parameters (DDP's - operational outcomes that matter to stakeholders beyond just cost and functionality, all inherent in the design. DDP's matter within all domains of engineering, and most require that domain expertise for their realization, with concentration on badly needed metrics, and measures.**

V. Extending Equivalence to the System Level

Equivalence as commonly defined and utilized in Engineering Economy is inadequate to support EE@SL.[8] The Design Evaluation Function (DEF) shown in Figure 5 (last entry) must and does encompass all phases of the system life cycle. This is illustrated in Figure 6. The DEF, incorporating both design dependent and design independent parameters, facilitates design optimization. It provides the basis for deriving the true difference between alternatives (a design-based choice) and optimization (an analysis-based choice).[2,8]

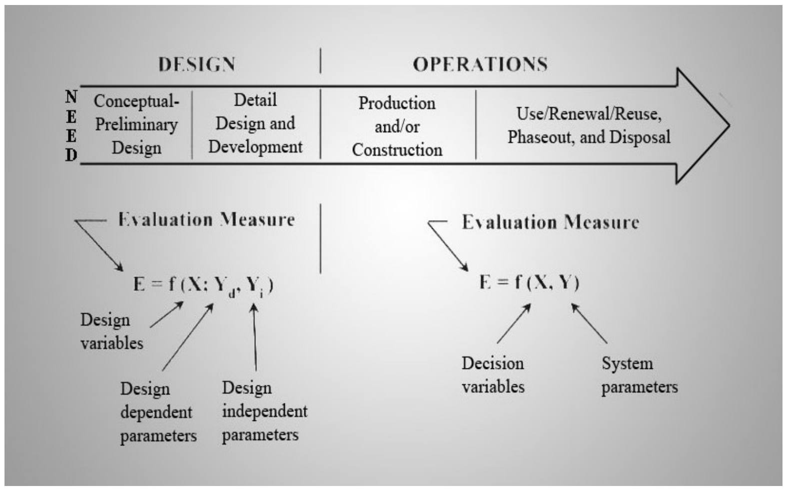

Figure 6. Evaluation functions mapped on the system life cycle

Two broad categories of analytical models are central to formulating an effective DEF for evaluating mutually exclusive system design alternatives. These are Money Flow Modeling and Economic Optimization Modeling.[5] These are shown in Figure 6 and derived next.

Money flow modeling. Central to the field of Engineering Economy are money flows over time. Engineering economics has always been associated with time; the time value of money, receipts and disbursements over time, etc. The central "model" in engineering economy is the money flow diagram, depicting estimates of income and outlay. Accordingly, EE and the product or system life cycle are on the same "dimension", one important avenue to EE@SL.

Algebraic expressions for the Present Equivalent (PE), Annual Equivalent (AE), and the Future Equivalent (FE), as well as expressions for the Internal Rate of Return and the Payback Period are well known in Engineering Economy. A general economic equivalence function subsuming each of these equivalence approaches is given in Figure 7.[8,11]

To Determine Economic Equivalence
Over the System and Product Life Cycle
Utilize the Economic Equivalence Function
PE, AE, or, FE = f (F_t, i, n)

Figure 7. Equivalence function for money flow modeling

Symbols in the money flow Equivalence Function are defined as follows:

F_t = positive or negative money flow at the end of year t
t = 0, 1, 2, . . . , n
i = annual rate of interest
n = number of years

The PE, AE, or FE amounts are consistent bases for the evaluation of a single alternative, or for the comparison of mutually exclusive alternatives. These bases for comparison are actually decision numbers, not budgetary amounts.

A disadvantage of money flow modeling is that Design Dependent Parameters are implicit, as are design variables. These are made explicit by economic optimization modeling as presented next.

Economic optimization modeling. Design evaluation in terms of life-cycle cost, benefit, and effectiveness at the system level can be facilitated by adopting the Design Dependent Parameter approach. This is a mathematical way to link design actions with operational outcomes. It utilizes a Design Evaluation Function (DEF) illustrated in Figure 8, with its heritage given in Figure 5.[2,8]

Mathematically Link Design and Operations
Utilizing the Life-Cycle Optimization Function
Equivalent LCC = f (X; Y_d, Y_i)

Figure 8. Equivalence Function with Economic Optimization

The definition of terms applicable to the general DEF in Figure 8 are:

E = a life-cycle complete evaluation measure such as equivalent life-cycle cost (PE, AE, or FE), Internal Rate of Return, Payout, etc.
X = design variables (e.g., number of deployed units, membrane thickness, retirement age, repair channels, rated thrust, pier spacing, etc.)
Y_d = design dependent parameters (e.g., weight, reliability, design life, capacity, producibility, maintainability, supportability, etc.)
Y_i = design independent parameters (e.g., energy cost, cost of money, labor rates, material cost per unit, shortage cost penalty, etc.

EE@SL Section V: Extending Equivalence to the System level

It should be noted again that the general Design Evaluation Function (DEF) is a combined equivalence approach with its genesis in monetary time value and economic optimization. There is nothing new here except recognition that Engineering Economy content and life-cycle mapping, as in Figure 6, have much in common. System thinking at a higher level is the key consideration, with EE@SL in mind.[6]

VI. Choosing the Preferred System Design

The Decision Evaluation Display (DED) method of making decisions in the face of multi-criteria is presented (and preferred for choosing from among mutually exclusive design alternatives - candidate systems). Some decision makers consider ranking, elimination, weighting, rating, and similar selection rules to be impediments to the effective application of insight, intuition, and judgment. An alternative is to put the emphasis on visually displaying and communicating only the differences upon which a decision depends, leaving the remaining path to a decision to the decision maker. The DED is such an alternative. Others are available in the litature.[3]

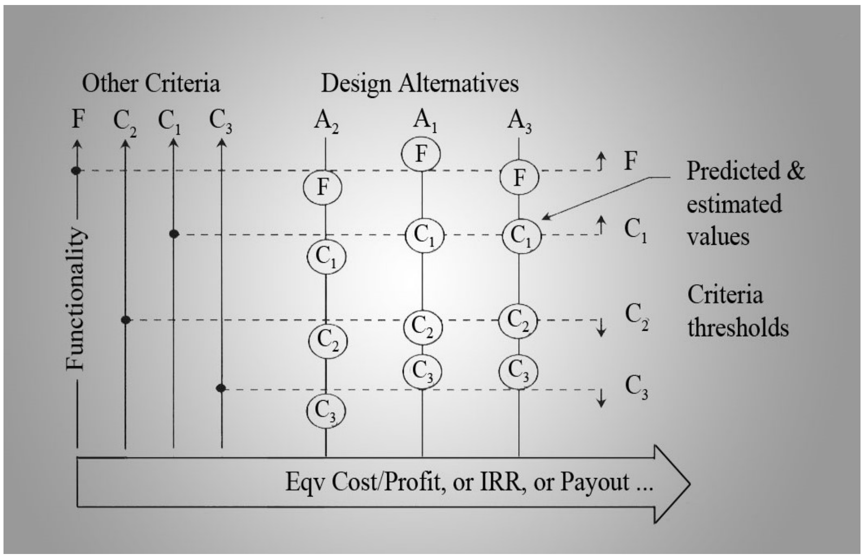

Figure 9. A Decision Evaluation Display for Multiple Criteria

The DED shown in Figure 9 is based on the premise that *differences between alternatives* and the *degree of compliance* with multiple criteria are all that most decision makers need or desire. Experienced decision makers possess an inherent and acquired ability to process needed information to trade-off competing criteria. Accordingly, the decision evaluation display is recommended as a means for simultaneously exhibiting the differences that multiple alternatives exibit in the face of multiple criteria.

Component parts of the Design Evaluation Display are explained below:

1) ***Alternatives (A_1, A_2, A_3).*** Two or more mutually exclusive alternatives appear as vertical lines in the field of the decision evaluation display.
2) ***Equivalent cost / profit, or IRR, or payout, etc.*** The horizontal axis represents present equivalent, annual equivalent, or future equivalent amounts. Specific values are indicated on the axis for each alternative displayed, with increasing values from left to right. In this way, equivalent life-cycle economic differences between alternatives are made visible.
3) ***Functional criteria (F).*** Functions individually, or all together represented by a derived index, appear at the far left of the vertical axes. Ordinal and/or cardinal scales may be utilized.
4) ***Other criteria*** **(*C_1, C_2, C_3*)** vertical axes represent one or more criteria, usually noneconomic in nature. Each axis has its own scale, depending upon the factor characteristics represented.

5) ***Other criteria thresholds.*** Horizontal lines emanating from all vertical axes represent threshold or limiting values for functional and noneconomic criteria (less than, equal to, or greater than).
6) ***Predicted and/or estimated values.*** Anticipated outcomes for each alternative (based on prediction and/or estimation) are entered by circles placed above, on, or below the thresholds. In this way, differences between desired and anticipated outcomes for each alternative are made visible.

Equivalent cost (or profit), calculated IRR, or Payout from Figure 7, or from a DEF combining them as in Figure 8, is shown on the horizontal axis of Figure 9, as objective economic measures. The decision aim is to select the mutually exclusive alternative with the lowest equivalent cost (or maximum profit, highest IRR, or lowest Payout) that adequately satisfies the other criteria.

Requirement thresholds are shown on the display. These are useful to the decision-maker in assessing the degree to which each mutually exclusive alternative meets functional and other criteria. This approach is recommended for most applications, because subjective evaluation by the customer and producer can be directly accommodated in a visible way. Trade-offs become visible and can be subjectively considered.

Multiple criteria considerations arise in life-cycle cost analyses during design when both economic and non-economic factors are present in the evaluation. Accordingly, design evaluation in terms of life-cycle cost or other economic metrics and system effectiveness is an area in need of attention by the producer and customer acting together. In this situation, a Design Evaluation Display, simultaneously exhibiting both cost and effectiveness measures can be quite helpful.

EE@SL Section VI: Bypassing Utility Functions and Theory

Decision makers face difficult decisions and must consider an increasingly wide range of criteria. In the past, such decisions were often judged only on the basis of a single attribute, such as cost or profit.

Significant work has been done to develop theory and related multiattribute utility models. The foundational work by Keeney and Raiffa (1976) is interesting, but difficult to employ at the system level. It is the desire to combine objective and subjective factors that causes this area of decision-making to be so elusive. EE@SL requires this combination making necessary the DED or something equivalent.

EE@SL requires a construct that captures and compactly displays the differences between mutually exclusive system design alternatives at each iteration of synthesis, analysis, and evaluation (Figure 2).

The construct of Figure 9 is recommended because of its compatibility with cost / benefit / effectiveness approaches of EE. It is also preferred because it incorporates visibly the host of design dependent parameters linking the human-made with its projected impact on the world in which we live.

Additionally, regarding EE@SL, the DED of this section, specifically Figure 9 or equivalent, is what EE should bring to the SL. Specific tie-in to the SL is contained in Block 9 of the System Design Morphology presented in Figure 4 of Section III.

VII. A Generic System Level Example (REPS)

Consider the following hypothetical but realistic situation: A finite population of repairable equipment units is to be acquired and maintained in operation to meet demand. As equipment units fail or become unserviceable, they will be repaired and returned to service. As units age, the older ones will be removed from the deployed population and replaced with new ones. The system problem is to determine the population size, the replacement age of units, and the number of repair channels for each set of design dependent parameter values in the face of design independent parameters so that stakeholder requirements will be satisfied at a minimum life-cycle cost.

Both the airlines and the military acquire, operate, and maintain aircraft with finite population characteristics. In ground transit, vehicles such as taxicabs, rental automobiles, and trucks constitute repairable equipment populations. Production equipment types such as machine tools, weaving looms, and autoclaves are populations of equipment known as producer goods. In housing, populations of dwelling units come into being after construction. All of the above, when deployed, become part of the human-modified world and are estimated to be a major part thereof.

The population system. A finite repairable equipment population system is designed and deployed to meet demand, *D*. Units within the system can be devided into two groups: those in operation and available to meet demand and those out of operation and hence unavailable to meet demand, as is illustrated schematically in Figure 10.

Two problem versions are treated in this system-level example. The first is to determine the population size, the replacement age of units, and the number of repair channels so that the sum of all life-cycle costs will be minimized. This is a problem of optimizing operations. It will be referred to as *REPS Optimization*. The second problem is to evaluate candidate system designs by predicting the unit mean time between failures (MTBF) and the unit mean time to repair (MTTR) as a function of unit cost, as well as other DDP's of customer and stakeholder interest. The derived optimal population size, the replacement age of units, and the number of repair channels is desired for implementation. This situation is referred to as a *REPS Design*.

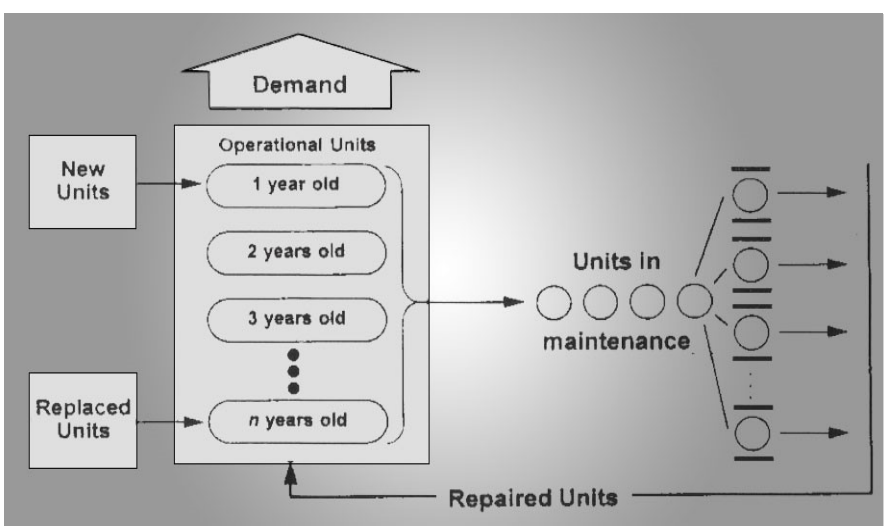

Figure 10. Reparable population system operations

In the REPS Optimization Problem, the decision consists of specifying a population size, a number of maintenance channels, and a replacement schedule for bringing new units into the system. For the REPS Design Problem, the decision scope is extended to include predicting design reliability and maintainability characteristics. In either case, the system is to be procured / designed to meet the demand for units in the face of multiple objectives, including intangible criteria.

Scope and assumptions. Repairable equipment population systems usually come into being over a non-steady state buildup phase. They then operate over a steady-state interval of years, after which phase-out is implemented. Only the steady-state mode of operation is considered here. As units age, they become less reliable and maintenance costs increase. Accordingly, it is important to determine the optimum replacement age. It is assumed that the number of new units procured each year is constant and that the number of units in each age group is equal to the ratio of the total number required in the population and the desired number of age groups.

Additional assumptions are adopted in the development of the model and algorithm for REPS: 1) The interarrival times are exponentially distributed, 2) The repair times are exponentially distributed, 3) The number of units in the population is small such that finite population queuing theory must be used, 4) The interarrival times are statistically independent of the repair times, 5) The repair channels are parallel and each is capable of similar performance, 6) The population size will always be larger than or at least equal to the number of service channels, 7) Each channel performs service on one unit at a time, 8) MTBF and MTTR values vary for each age group and represent the expected value for these parameters for that age group, 9) Units completing repair return to operation with the same operational characteristics as their cohort group.

Demand is the primary stimulus on repairable equipment population systems and the justification for their existence. This uncontrollable system parameter is assumed to be constant over time. Other uncontrollable system parameters are economic in nature. They include the shortage penalty cost arising when there are insufficient units operational to meet demand, the cost of providing repair capability, and the time value of invested capital.

Evaluation function formulation. An evaluation model for REPS can be formulated using the *Equivalence Function with Economic Optimization* form as presented in Figure 8. Choosing annual equivalent life-cycle cost as the economic measure of interest stated as:

AELCC = PC + RC + SC with

1) Population Annual Equivalent Cost: PC = $C_u N$ where $C_u = (P - F)(\ ^{A/P,i,n}\ ) + F(i)$
2) Repair Facility Annual Equivalent Cost: RC = $C_r M$
3) Annual Shortage Cost: SC = C_S [E(S)] where $E(S) = \sum_{j=1}^{D} jP_{(N-D+j)}$

Much of the required mathematics is omitted but may be found in the cited references. E(S) is derived from finite population queueing theory with $P_{(N-D+j)}$ being the probability of shortage that will range from 0 to D units.[2,9] Alternatively values may be taken from the Peck and Hazelwood *Finite Queuing Tables*. A condensed set off these tables is found in Appendix F of Systems Engineering and Analysis.[2]

REPS variables and parameters. REPS variables and parameters (design dependent /independent) are summarized in Table 1. These provide insight about finite populations of repairables and indicate the value of the DDP paradigm as was presented in Section IV. Then a hypothetical example will be used for REPS Optimization and then for REPS Design.

Table 1. Design Variables and System Parameters for REPS

Variables / Parameters	Design Variables	Design Dependent	Design Independent
D = Demand for deployed units			x
N = Number of units deployed	x		
M = Number of maintenance channels	x		
n = Retirement age of deployed units	x		
C_u = Annual equivalent unit cost per unit		x	
C_r = Annual channel cost per channel			x
C_s = Shortage cost per unit short per period			x
MTBF = Mean time between unit failure		x	
MTTR = Mean time to repair a unit		x	
EI = Environmental Impact Index		x	

REPS Optimization. Here the objective is to find optimal values for controllable design variables in the face of uncontrollable system parameters. In REPS Optimization, the decision evaluation function is used to seek the best candidate system. This is accomplished by assuming design-dependent parameters to be fixed or uncontrollable, locked in the design. Uncontrollable design-independent parameters are locked in by the economic and geographic setting.

In the optimization problem the focus is entirely on optimizing design variables as the only controllable factors. This situation arises when the system is in existence and the objective is to optimize its operation in the face of (uncontrollable) system parameters. The focus shifts to seeking the best candidate system in the REPS design problem. In this activity, optimal values for design variables are sought. They are needed as a means for comparing candidate systems equivalently, with the time value of money and economic optimization considered. When the best system is identified, specific values of decision variables are implemented to assure its optimal operation.

REPS Design. Assume that the demand, *D*, is for 15 identical equipment units. Table 2 summarizes the design variables and system parameters for REPS. Note that the design dependent parameters of unit cost (C_u), reliability (MTBF), and maintainability (MTTR) are essentials.

Some system parameters are uncontrollable in REPS Optimization, but controllable in the REPS Design Problem. These are the design MTBF and MTTR, the environmental impact of deployed units, the design life of units, and the first cost and salvage value of deployed units. It is through these design-dependent parameters that the best candidate system may be identified.

Consider a REPS design alternative to the optimization baseline for which the decision variables and system parameters are shown in Table 2. REPS presents an operations improvement opportunity if the system is already in being; that is, if design dependent parameters are not any longer in the design stage. A system design problem exists if a REPS system is being brought into being. Design Dependent Parameter values are in play during the design process.

Table 2. System Parameters for REPS

Variables / Parameters	Optimization	Design
Demand	15	15
Annual shortage cost	$73,000	$73,000
Annual interest rate	10%	10%
Cost of equipment unit*	$52,000	$43,000
Salvage value per unit	$7,000	$5,000
Design life (years)	6	6
Repair channel cost (per channel)	$45,000	$45,000
Average MTBF (years)*	0.25	0.22
Average MTTR (years)*	0.05	0.05
Environmental Impact Index	< ML	< M

Table 3 gives a summary of the optimization results for effectiveness measures (cost and shortages) and system design variable values. From this it is evident that the optimization baseline candidate is best on the basis of life-cycle cost alone. However, the design is best for the probability of one or more units short, as well as on the average MTBF value (see Table 2).

Table 3. Optimized Outputs for REPS

Calculated Output	Optimization	Design
Population cost / operating	$221,616 / 33,250	$202,804
Repair facility cost	$135,000	$180,000
Shortage penalty cost	$73,484	$47,668
Expected (AELCC)	$463,350	$468,825
Probability of > one short	0.62	0.73
Mean units short	1.0066	0.6530
Mean units down	3.15	4.36
Total number of units deployed	19	20
Repair channels	3	4
Retirement age	4	4

Optimum design variable values are shown in the last three rows of Table 3. These are the number of units to procure (N), the number of repair channels to provide (M), and the retirement age for deployed units (n). These will be used to implement optimal REPS operating policy for the system design yet to be chosen. For example, assume that the design constraints and requirements are:

1) Design to cost - the deployed population shall have a first cost that does not exceed $900,000.
2) Probability of shortages - the probability of one or more equipment units short of demand shall not exceed 0.30.
3) Reliability - the mean time between failures for deployed units shall be greater than 0.2 years.

Selection of the best alternative (candidate system) in the face of design requirements is facilitated by the Design Evaluation Display illustrated in Figure 11. Noted therein is the violation of the population cost by the Baseline (opt) alternative. Both candidates meet the reliability(MTBF) requirement, but Baseline violates the probability of one or more units short of demand.

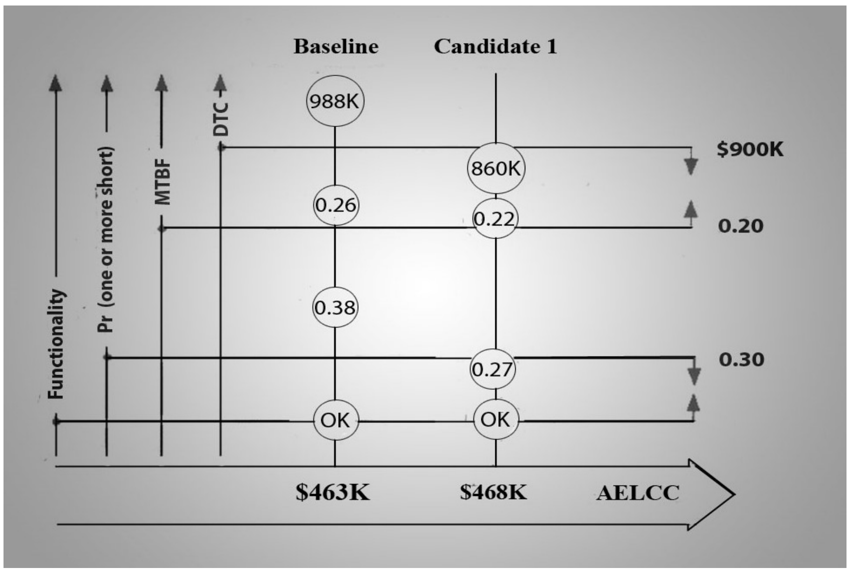

Figure 11. Design evaluation display for REPS example

REPS calculations (see Reference 2 pages 635-642) provide decision variable values and other factors for subjectively comparing the alternative candidates. Figure 12 gives one of these. The probability of one or more short is satisfied only by Candidate 1. Information from the shortage probability histogram is entered on the DED adding to its usefulness in customer decision making.

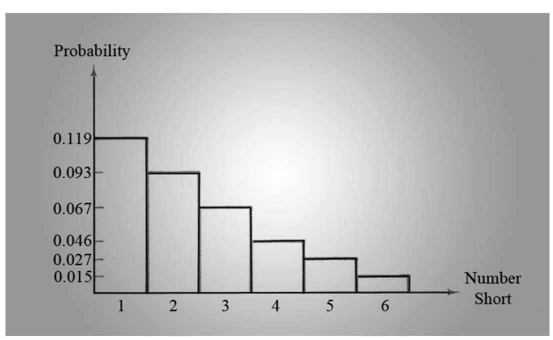

Figure 12. Probability of one or more units short

EE@SL connections within REPS. Connections to the system level abound in the REPS example of this Section VII. As a final exercise, see if you can list a few that are of greatest interest to you.

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