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Engineering Design in Integrated Product Development
Management of Design Complexity

ADDRESSING DESIGN COMPLEXITY: INTEGRATING PRODUCT LIFE CYCLE AND PRODUCT PORTFOLIO CONSIDERATIONS

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Abstract: *Design complexity, from the perspective of the producer, derives from the desirability of focusing on what the product does before determining what the product is, with form following function; designing for the product life cycle, yet recognizing the concurrent life-cycle factors for production, support, phaseout; and disposal; integrating and iterating synthesis, analysis, and evaluation; and structuring, populating, and evaluating the product portfolio periodically over a planning horizon. In this paper, these considerations are addressed as part of an integrated product realization process intended to maximize profitability and the future worth of the firm. The process focuses on choosing the right products to design (by product portfolio analysis) and on doing the product designs right (by product design evaluation).*

1. INTRODUCTION

An important activity within any commercial firm is the allocation of engineering and supporting resources to enable the design, development, production, distribution, support, and phase out of products over their life cycles. The goal of this activity should be to allocate resources to products (projects) in the best possible way, so that the firm's profitability and future worth will be maximized.

Commercial firms generally do not have an effective procedure in place for allocating scarce resources to products. Most of the managerial, engineering, and design effort is directed to individual products. There is usually little formal attention given to the competition for development resources among products as they go through the design and utilization phases of their life cycles.

Accordingly, this paper will: (1) review the decision process for choosing the preferred design from among the large number of design alternatives that may be generated for a single product, including recognition of the resources consumed and, (2) describe viable methods for selecting the best portfolio of products that should be authorized at any given point in time. It is important in practice to do both (1) and (2) concurrently; but (2) should take precedence over (1).

2. SYSTEMS ENGINEERING

Systems engineering (SE) is a technologically based interdisciplinary process for bringing products, systems, and structures into being (1). SE can help in doing the product design right and in designing the right product(s). While the main focus is nominally on the entities themselves, SE embraces a better strategy. Systems engineering concentrates on *what the entities do* before determining *what the entities are*. That is, instead of offering products, systems, or structures per se, the organizational focus should shift to designing, delivering, and sustaining functionality, a capability, or a solution.

The overarching purpose of systems engineering is to make the world better for people. People-made entities should be designed to satisfy human needs effectively, while minimizing life-cycle cost for the customer, as well as the intangible external costs of ecological and societal impacts. In doing system design and development, it is essential that the resources required be identified and projected over the system life cycle. Resource projection by product makes it possible to determine which new products should be added to the product portfolio, which existing products should be continued, and which products should be discontinued. Profit maximization will surely follow if the right products are selected and then designed right.

3. LIFE-CYCLE RESOURCE COSTS

Resources consumed over the life cycle of the product or system generate costs; the determination thereof is called life-cycle costing (3). Life-cycle costing is an essential step in determining system cost-effectiveness and/or product profitability. It is one factor in deciding if the design is done right.

Due to its importance of life-cycle costing in design evaluation, and the importance of evaluation in doing design right, this activity will be emphasized in Section 4. Life-cycle costing is also essential in the creation of product portfolios. The application of portfolios in determining the right products to select for design is emphasized in Section 5.

3.1. The Cost Breakdown Structure

Resources applied over the system life cycle generate costs that fall into general categories based on the activities needed to bring the product, system, or structure into being. The categories and their subordinate elements constitute a Cost Breakdown Structure (CBS), as illustrated in Figure 1.

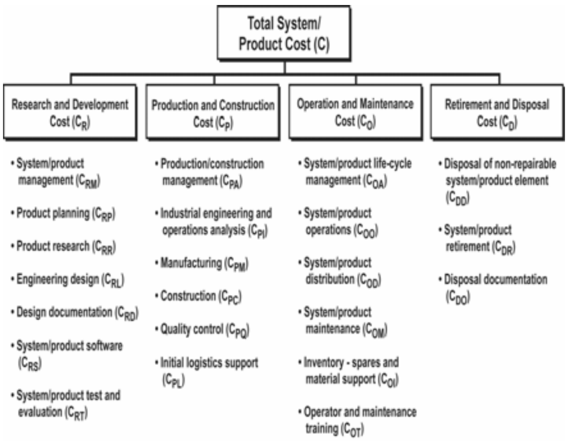

Figure 1. *A General Cost Breakdown Structure*

The CBS links objectives and activities with organizational resource requirements. It constitutes a logical subdivision of cost by functional activity area, major system elements, and/or one or more discrete classes of common or like items. The CBS provides a means for initial resource allocation, cost monitoring, and cost control. The four main CBS categories are described next:

3.1.1. Research and development cost

The cost of initial planning, market analysis; feasibility studies; product research; requirements analysis; engineering design; CAD/CAM equipment and software, design data and documentation; the test and evaluation of models; and associated management functions make up research and development costs. Included in this category should be the costs of environmental impact studies.

3.1.2. Production and/or construction cost

Costs of manufacturing (fabrication, assembly, and test); facility construction; industrial engineering and operations analysis; process development; production operations; quality control; and logistic support (e.g., initial consumer support, the manufacture of spare and repair parts, the production of test and support equipment, etc.).

3.1.3. Operation and support cost

Costs arising from consumer or user operation of the system or product in the field; product distribution (marketing and sales, transportation, and traffic management); and sustaining maintenance and logistic support throughout the product life cycle (e.g., customer service, maintenance activities, supply support, test and diagnostic equipment, transportation and handling, technical data, facilities, product modifications, etc.).

3.1.4. Phase out and disposal cost

Cost of system or product retirement and phase out; disposal of non-repairable items; material recycling; and applicable logistic support needs are included in this category. Not to be overlooked are intangible costs arising from environmental impacts. This should include the disposal of waste generated during product production and operation.

3.2. Life-Cycle Cost Profiles

With the Cost Breakdown Structure defined and cost estimating approaches established, it is appropriate to apply the resulting data to the product life cycle. To accomplish this, cost profiles are developed which include aspects of inflation, the effects of learning, etc. The following steps are essential:

Identify all resource consumption activities over the life cycle that will generate costs of one type or another. This includes the functions associated with planning, research and development, test and evaluation, production and/or construction, product distribution, system or product operational use, maintenance, logistic support, phase out, etc.

Relate each activity identified above to a specific cost category in the Cost Breakdown Structure in Figure 1. All program activities should fall into one or more of the CBS categories and all categories should be represented.

Establish the appropriate cost factors in constant dollars, for each activity in the CBS, where constant dollars reflect the general purchasing power of money at the time the decision is being made (i.e., today). Individual cost elements within each cost category of the CBS are then projected into the future on a year-to-year basis over the life cycle.

For each cost category in the CBS, and for each applicable year in the life cycle, introduce the appropriate inflationary factors, effects of learning, changes in price levels, and so on. The modified values constitute a new cost stream and reflect realistic costs as they are anticipated for each year of the life cycle. These costs may be used directly in the preparation of future budget requests, since they reflect the actual dollars needed to meet the resource requirements over the life cycle.

Next, summarize the individual cost streams by major categories in the CBS and develop a top-level cost profile. Results from the foregoing sequence of steps are presented in the upper part of Figure 2.

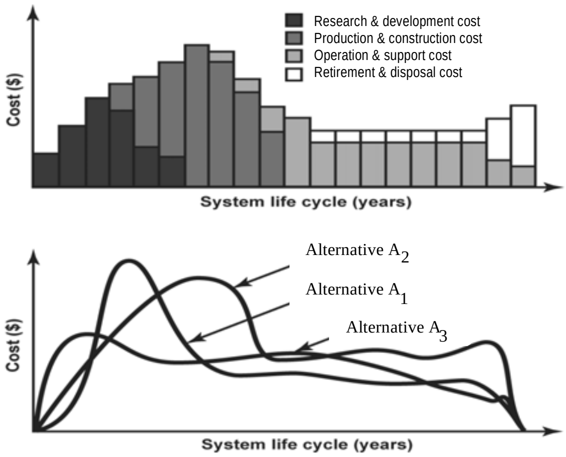

Figure 2. *Life-Cycle Cost Profiles*

First, it is possible and often beneficial to evaluate the cost stream for individual activities of the life cycle such as research and development, production, operation and support, and so on. Second, the individual cost streams may be shown in the context of the total cost spectrum. Finally, the total cost profile may be viewed from the standpoint of the logical flow of activities and the proper level and timely expenditure of money.

The profiles in the lower part of Figure 2 represent a budgetary estimate of future resource needs for each design alternative and may be used in the selection of the best alternative. Once the best alternative is selected, the applicable profile is used to populate the product portfolio within the firm. Discussion of this use of the cost profile will be deferred until Section 5, where product portfolio analysis is presented.

When dealing with two or more candidate design alternatives, each will include different levels of activity, different design approaches, different logistic support requirements, and so on. No two candidate design configurations will be identical. Thus, individual profiles will be developed for each alternative and then compared on an equivalent basis, utilizing the economic analysis methods introduced in the next section

4. DOING THE DESIGN RIGHT

Design requires both integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation. System design is the backbone of systems engineering, with system design evaluation as its compass. The end result should be a product, system, or structure that is designed right (1).

Products and systems seek to satisfy identified needs or defined objectives. Effectiveness is the degree to which needs and objectives are met. But, need satisfaction incurs a total cost to the user over the life cycle. Thus, both cost and effectiveness must be considered jointly during system design and development. Emphasis is placed on life-cycle cost and revenue analysis, within the context of system effectiveness, as driven by design dependent parameters (DDP's). The aim is to provide insight into the elements and process for considering both cost and effectiveness jointly (3).

4.1. Identifying Evaluation Criteria

Evaluation criteria must be identified and selected for comparing both the life-cycle cost and the effectiveness aspects of the candidate designs under consideration. Some common evaluation criteria are illustrated in Figure 3.

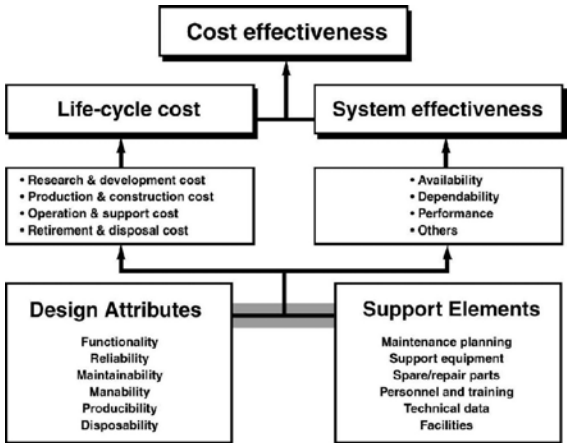

Figure 3. *Criteria for Cost-Effectiveness Evaluation*

Among the important categories of cost are those elements arising throughout the product life cycle. These include the costs associated with design development, production, operation, support, and phase out and disposal, as is shown on the left side of Figure 3.

Effectiveness is a measure of mission fulfillment for a product or system in terms of a stated need. Mission fulfillment may be expressed by one or more figures of merit, depending on the type of product or system and the objectives to be achieved. Some common effectiveness measures are shown on the right side of Figure 3.

Evaluation criteria for effectiveness are usually quite difficult to establish. Most products and systems have multiple purposes that complicate the situation further. General effectiveness categories are utility, merit, worth, benefit, and profit. Some of these cannot be easily quantified, so criteria such as functionality, reliability, maintainability, availability and others are normally used.

Ordinarily, less difficulty exists in establishing cost and revenue profiles than in establishing criteria for effectiveness. Nonetheless, both aspects should be considered jointly during product or system design and development.

4.2. Considering Multiple Criteria

Multiple criteria considerations arise in life-cycle cost analyses during design when both economic and non-economic elements are present in the evaluation. Accordingly, design evaluation in terms of life-cycle cost and system effectiveness is an area in need of attention by the producer and customer jointly. In this situation, a Design Evaluation Display (DED), simultaneously exhibiting both cost and effectiveness measures, can be helpful. The general version presented in Figure 4 is suggested.

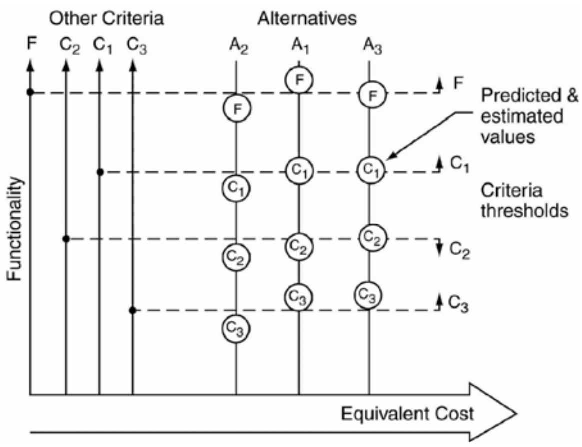

Figure 4. *The Design Evaluation Display*

Life-cycle cost, shown on the left side of Figure 4 and one or more effectiveness measures may be displayed simultaneously as an aid in decision making. The DED exhibited in Figure 4 is a suggested way of doing this. Note that effectiveness requirements or thresholds are shown on the display. These are useful to the decision-maker in assessing the degree to which each design alternative meets decision criteria. This approach is recommended for most applications, because subjective evaluation by the customer and producer can be directly and visibly accommodated.

Product competitiveness is imparted during system design and development, where attention directed jointly to life-cycle cost and effectiveness matters most. For the best outcome, the producer or contractor should engage the customer in design decision making early in the life cycle. This can be accomplished more easily when all relevant factors are displayed in a consistent manner for each system design alternative being considered. The cost-effectiveness comparison can then be made by the customer based on subjective evaluation; beauty being in the eye of the beholder.

4.3. Calculating Economic Equivalence

Economic equivalence is essential to the comparison of mutually exclusive design alternatives on a "fair" basis; essential to the accurate placement of each alternative on the horizontal axis of a Design Evaluation Display of Figure 4. Equivalence is achieved when money flows over time (costs or profit) are reduced to a common economic base by one, or a combination of, the following paradigms: 1) Money Flow Modeling; 2) Economic Optimization Modeling. These are presented next.

4.3.1. Money flow modeling

Money flow modeling is central to the field of engineering economics . Engineering economics has always been associated with time; the time value of money, receipts and disbursements over time, etc. The central "model" in engineering economics is the money flow diagram, depicting estimates of income and outlay (revenue and cost) over time (3). Thus, engineering economics and the product or system life cycle are on the same "dimension", producing profiles like those shown in Figures 2.

Mathematical expressions for Present Equivalent (PE), Annual Equivalent (AE), and Future Equivalent (FE) amounts, as well as expressions for the Internal Rate-of-Return (IRR) and the Payback Period (PP) are well known in engineering economics (2) (3). A general economic equivalence function, subsuming each of these equivalence approaches, is given in Figure 5. Symbols in the 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

To Derive Cost Equivalence

OVER THE PRODUCT LIFE CYCLE

Utilize the Economic Equivalence Function

PE, AE, or, FE = f (F_t, i, n)

Figure 5. *Equivalence Function for Money Flows*

The Present Equivalent, Annual Equivalent, and Future Equivalent 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 or impacts. They are the values entered on the horizontal axis of the Design Evaluation Display for each of the alternatives being compared.

4.3.2. Economic optimization modeling

One disadvantage of money flow modeling is that Design Dependent Parameter values are implicit, as are design variables. These are made explicit by economic optimization modeling (3).

The following definitions of terms and symbols apply to the Design Evaluation Function in Figure 6.

To Derive an Economic Optimum

LINK DESIGN AND OPERATIONS

Utilizing the Design Evaluation Function

$$E = f\,(X;\,Y_d,\,Y_i)$$

Figure 6. *DEF for Economic Optimization*

E = a life-cycle complete evaluation measure such as equivalent life-cycle cost or profit (PE, AE, or FE)

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, maintainability, design life, capacity, producibility, polutability, etc.)

Y_I = design independent parameters (e.g., energy cost, cost of money, labor rates, material cost per unit, shortage cost penalty, etc.)

The DEF must be linked to all phases of the system life cycle. This function, incorporating both design dependent and design independent parameters, facilitates design optimization. It provides the basis for a clarification of the truer difference between design alternatives (a design-based choice) and optimization (a search-based choice).

Design dependent parameters are characteristics inherent in the product or system design. They are subject to control by the designer, or design team, during the process of seeking the best design. Each instance of the DDP values identifies a mutually exclusive design alternative and provides the basis for design evaluation, utilizing a Design Evaluation Display or equivalent.

5. DOING THE RIGHT DESIGN(S)

Ordinarily there will be a number of different products being designed, developed, and marketed by the firm. It is assumed, at this point, that each product is being designed right by utilizing the methodology presented in Section 4, or its equivalent. That is, assume that the design of each product is being subjected to a continuous product evaluation process, including use of a DED or similar display to the customer.

5.1. The Product Portfolio

A product portfolio exists within the firm when two or more products are in existence. When this is the case, scarce resources are allocated to the products with the anticipation of returns greater than the costs thereof. The objective is to determine the most profitable portfolio to have in existence at any point in time, so that the future wealth of the firm may be maximized. That is, a mix of the right products to offer is sought by product portfolio analysis.

Figure 7 illustrates a hypothetical product portfolio, with product life cycles shown by simple resource profiles. Negative, 'below the line' profile segments indicate resources being incurred at a cost. Positive, 'above the line' profile segments indicate net returns. Note that the 'Today' line partitions each product into its past (with sunk cost revealed) and its future (based on cost and net revenue estimates). Portfolio evaluation, intended to select the right set of products at any point in time, is done only over the portion of the life cycle to the right of the 'Today' line.

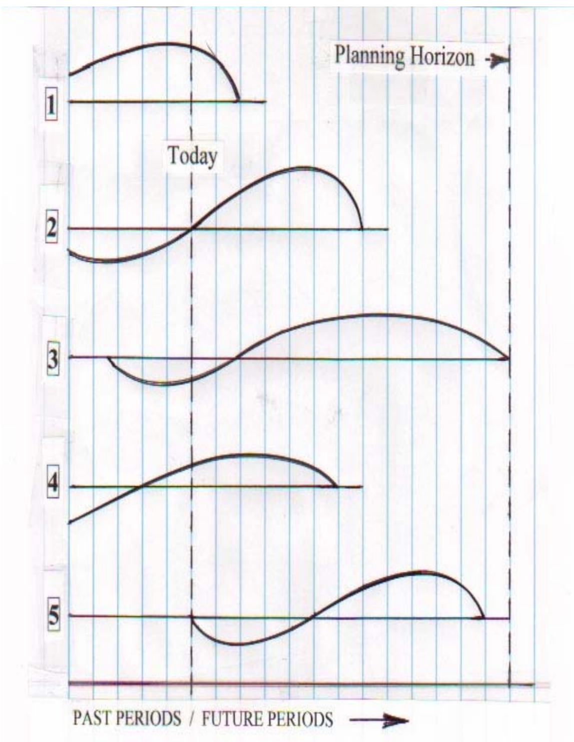

Figure 7. *A Hypothetical Product Portfolio*

All products under consideration in the portfolio need not have the same life; unequal lived products may be accommodated, as illustrated in Figure 7.

Available products may have their resource consumption needs and net revenue flows estimated in accordance with discrete or continuous functions. In Figure 7, continuous functions are utilized and described for each product:

Product 1 was designed and developed several periods ago. It continues to generate significant net revenue that is just now beginning to decline.

Product 2 has just completed its design and development phase and is to begin generating net revenue in the next period.

Product 3 is completing estimated expenditures in the next two periods, after which it is expected to generate a long-term net revenue flow. This product is the longest lived in the portfolio and it will define the planning horizon for portfolio analysis.

Product 4 has just entered its revenue-generating phase, with its design and development costs having ended two periods ago.

Product 5 is being considered as a new project. It has an anticipated design and development cycle spanning five periods, to be followed by a net revenue cycle over seven periods.

5.2. Resource Allocation to Products

Resource allocation to products is conducted in a dynamic resource constrained environment. In each period of the process, only estimated values are available for product costs, product net returns, and system parameters. Product interdependencies must also be considered in allocating the firm's limited capital among the active products in the portfolio.

Each designer (or design team) should be required to periodically provide anticipated resource consumption needs to the product portfolio manager. The designer should report estimates of the life-cycle cost elements by period, in accordance with the cost breakdown structure of Figure 1. These estimates should derive from the design and from the anticipated resources required to develop, produce, distribute, support, and dispose of the product. Then, in cooperation with marketing, the anticipated revenue stream should be reported. With this information, the portfolio manager can continuously determine if the right products are being developed, marketed, and distributed.

It is important to recognize that decisions made in the present affect investments of resources, which are to be made in the future. Decisions to invest in products now result in the absorption of resources that could have been held over and allocated to products that might contribute a higher equivalent value to the portfolio.

5.3. Product Funding Over Time

Upon completing the resource allocation in one period, the chosen products are funded until the end of the period. These products are then considered, along with new product initiatives, and the process is repeated. This activity makes the resource allocation decision in one period only one of a long series of such decisions.

At each decision point, two types of products must be considered; those that are ongoing and those that have not yet been initiated (project not yet established). For ongoing products, the portfolio manager must decide if a product in the portfolio should receive increased funding, decreased funding, unchanged funding, or no funding at all (product cancellation). These decisions will dynamically alter the cost and revenue profiles for the products that were shown in Figure 7.

Various constraints are usually present. These may include mutual exclusivities, contingencies, and resource limitations. The decision may also be constrained by non-economic factors such as a requirement that a certain product be included in the ongoing portfolio, regardless of its economic viability. This is a "must fund" requirement.

5.4. A Portfolio Creation Process

To correctly consider an allocation decision when n products are available, the portfolio manager must analyze 2 to the n-th power different product combinations. The resource allocation decision is not only large in scope, but it is conducted in a dynamic environment that changes from decision period to decision period.

Figure 8 presents a conceptual flow diagram for portfolio creation and evaluation. It was adapted from reference (6) and is included here to provide a view of the intricacy of the process. The process has ten distinct steps summarized below:

1. Input parameters – the number of products, the cost of capital, the minimum acceptable rate of return, the budget limitation, and the end point of the longest lived product.
2. Input product cost and revenue estimates – use functions with shape parameters to pattern cost and revenue profiles.
3. Output possible portfolios – an exhaustive zero-one matrix is generated.
4. Input mutual exclusivities – if any exist, they act to eliminate infeasable portfolios from the zero-one matrix.
5. Input contingencies – if any exist, they act to eliminate infeasable portfolios from the matrix.
6. Input must-choose constraints – if any exist, the portfolios in the zero-one matrix that do not contain the essential product are eliminated.

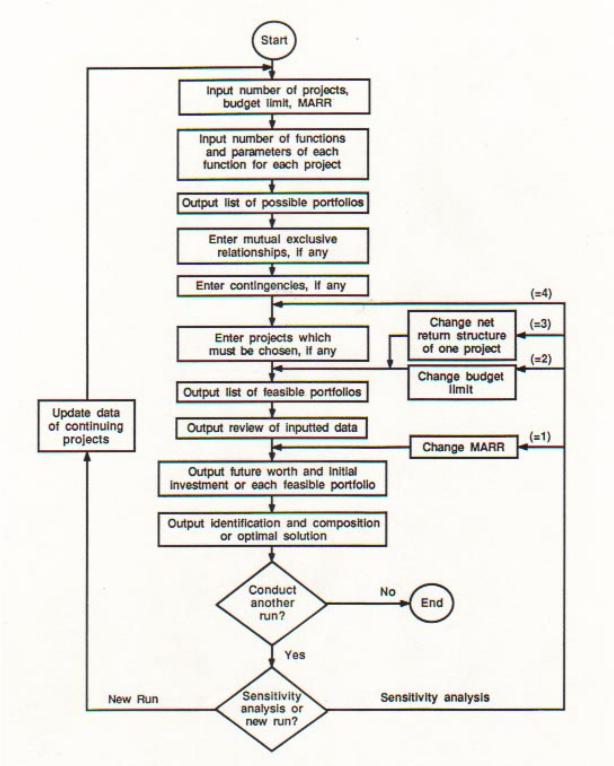

Figure 8. *Portfolio Generation Process*

7. Output feasible portfolios – a budget constraint, if active, acts to further eliminate portfolios. Remaining portfolios are displayed.
8. Review product data – cost and revenue estimating relationships are displayed for review and alteration, if sensitivity analysis is to be done.
9. Output future worth – the future equivalent worth is provided for feasible portfolios so that the optimal portfolio can be identified.
10. Do another run – if desired, four types of sensitivity analyses may be conducted.

5.5. Methods of Portfolio Selection

There are three main methods for determining the best mix of products to have in the portfolio at any point in time. These are briefly discussed below.

5.5.1. Heuristic portfolio selection

A heuristic or empirical method of portfolio selection is often used because of its simplicity. It is based on an informal connection between product design and development people and management. This method depends upon judgment involving interaction between designers and management. Analytical methods, models, and computer aided tools is usually minimal. This approach works best for small firms offering few products.

5.5.2. Selection by rank on rate-of-return

Rank on rate-of-return (ROR) is a formal analytical method that uses money flow modeling in accordance with Figure 5. The computation for ROR is based on cost profiles and anticipated net revenue projections on a product-by-product basis.

The budget impact caused by each product must be listed along with the ROR. This information is then gathered periodically as a basis for selecting the portfolio for the next period. Some products will not be initiated and others will be discontinued because their ROR falls below the minimum acceptable rate of return (MARR). This portfolio selection method is easily explained and is somewhat rigorous (2).

5.4.3. Selection by portfolio future worth

The method in Section 5.4 was based on the future equivalent (FE) worth criterion (Figure 5 showed the applicable mathematical form). The procedure presented there utilized the future equivalent worth of net return criterion in making a recommended product portfolio selection. Selection of a preferred portfolio requires the creation of an exhaustive zero-one matrix of product possibilities, with reduction in the number of portfolios accomplished by the application of one or more constraints (6).

The best product combination is determined from the feasible set by calculating the FW based on a MARR during the life of each product, and moved to the end of the planning horizon utilizing the cost of money. This is a rigorous and cumbersome selection method.

6. SUMMARY AND CONCLUSIONS

The theme of this paper is design complexity from the perspective of the firm, not just from the perspective of the product. Design complexity, as addressed herein, derives from the desirability of doing the design right and also from doing the right design. Thus, design complexity results from looking beyond the design of individual products.

It is relatively simpler to do a design right if the interactions between product designs are ignored. In this commonly adopted situation the designer, or design team, does not need not be concerned about the issue of doing the right design. Neither is it necessary to be concerned about the best allocation of resources to the product and its realization process. Although this narrow view is tempting, it is usually not best for the long-term wealth of the firm.

Finally, the widely used concept of deriving cost flows per product (project), also used in this paper, has serious weaknesses when resources are shared by different products. Cost allocation is the problem. However, it is possible to avoid cost allocation to competing activities if a special portfolio approach is used, one where costs are considered only in the acquisition and utilization of resources. This special approach is an extension to the method of this paper and is offered for consideration in reference (5).

GLOSSARY

Cost breakdown structure - a cost hierarchy linking objectives and activities with organizational resources requirements.

Cost effectiveness - a methodology for jointly considering cost and effectiveness incorporating subjective evaluation.

Design dependent parameter - a characteristic inherent in the design (e.g., reliability, maintainability, etc.).

Design evaluation - to compare a candidate design against other candidates checking for compliance with customer requirements.

Design evaluation display - a graphical means of simultaneously exhibiting both cost and effectiveness measures.

Design evaluation function - a mathematical expression linking specific design dependent parameter values with operational outcomes.

Design independent parameter - a factor external to the design (interest rate, fuel cost per pound, etc.).

Equivalence - a common economic base obtained by money flow modeling or economic optimization modeling.

Evaluation criteria - factors selected for comparing both the life-cycle cost and the effectiveness aspects of candidate designs.

Life-cycle cost – an aggregate of all costs incurred over the lifer cycle of the product or system.

Life-cycle cost profile – a graphical display of the magnitude of cost over the life cycle.

Money flow diagram - a graphical exhibit of estimates of income and outlay over time for an alternative.

Product portfolio – one combination of products from among all possible combinations of those products.

Systems engineering - a technologically based interdisciplinary process for bringing systems, products, and structures into being.

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