SIMULTANEOUS ENGINEERING DESIGN EVALUATION USING THE DESIGN DEPENDENT PARAMETER APPROACH

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
Industrial and Systems Engineering

APPROVED

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February, 1995
Blacksburg, Virginia

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(ABSTRACT)

This thesis presents a computer based simultaneous engineering design evaluation methodology to simultaneously evaluate candidate product and manufacturing resource designs. It utilizes the design dependent parameter approach to evaluate design alternatives resulting from candidate product and manufacturing resource designs. The evaluation measure used is expected profit.

A linear, mixed integer, single period, simultaneous engineering design evaluation model is developed to evaluate design alternatives, comprising candidate product and manufacturing resource designs, using a design evaluation function. The design evaluation function utilizes a linear optimization based search to evaluate each design alternative.

An integrated menu based software application, called SEDE 1.0, is developed to implement the design evaluation model. It integrates XPRESS-MP, a modeling language and solver, and Paradox 3.5 for DOS, a relational database management system. The application provides for ease of data handling in that input data is entered, edited, manipulated, and stored in Paradox tables. It is then read directly by the modeler at the time of matrix generation.

The design evaluation model is then applied to the constrained-design problem wherein the design alternatives for the products as well as the production resources are limited. In this case, a complete, a priori, enumeration of all feasible design alternatives is possible. The constrained-design evaluation model includes design alternatives for both, products as well as manufacturing resources. It merges the design space into the optimization space.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Wolter J. Fabrycky, whose inspiration, guidance, and patience were invaluable throughout this thesis endeavor. I would also like to thank the other members of my committee, Dr. Subhash C. Sarin and Dr. George C. Moolman, for their continued support and contribution to this thesis.

A big thank you goes to my parents for their support and encouragement, always, which made it all possible. I would also like to thank my sponsors, Gujarat Sulphites Ltd..

The computational work was performed with support from the Systems Engineering Design Laboratory and the Simulation and Optimization Laboratory in the Department of Industrial and Systems Engineering at Virginia Tech.

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1.0 INTRODUCTION

This thesis presents a methodology and models for the evaluation of alternative product and manufacturing resource designs generated during simultaneous (or concurrent) engineering design activity. The simultaneous engineering design evaluation models developed in this thesis could help simultaneous engineering design teams compare candidate product and resource designs on the basis of expected profits that would be generated by the implementation of the product and resource design configuration. It is suggested that profit maximization is one of the most important objectives of a firm and is, therefore, a suitable basis for design evaluation.

1.1 Simultaneous Engineering Background

Traditionally, the design of products and the design of required production resources in a manufacturing firm have taken place sequentially. A sequential design process not only results in longer product lead times, but also essentially determines the manufacturing cost at the product design stage itself. A drastic reduction in these costs is not possible at the process design stage [Yoshimura, 22].

The need for technical and economic competitiveness in today's global economy has brought about changes aimed at reducing product manufacturing costs, while increasing the value of products so as to increase marketability. Manufacturers are now focusing on life-cycle complete engineering. This life-cycle design approach involves consideration of the life cycle of not only the product, but of the manufacturing resources as well. Several business philosophies, designed to help manufacturers achieve these goals, have emerged in recent years. Among these is simultaneous or concurrent engineering, which is the focus of this research.

Kalpakjan [11, p. 16] defines simultaneous engineering as "a systematic approach that integrates the design and manufacturing of products with the view of optimizing all aspects involved in the life cycle of the product, including costs, quality, scheduling, and the ultimate disposal of the product". Thus, simultaneous engineering requires the integration of the product development processes with the design and implementation of production processes. In the simultaneous engineering environment, product designers need to consider manufacturing aspects such as tooling, routing, and assembly when designing the product.

The primary benefits derived from implementing simultaneous engineering are enhanced product value, increased customer satisfaction, and reduced time to market. All of these help improve financial performance of the products and hence of the company. The importance of getting products designed efficiently and rapidly and into the market quickly is highlighted by a study undertaken by Mc Kinsey & Co. to examine the impact of product time-to-market on the bottom line. The results of the study showed that "being late to market is ten times worse than spending 50% more than planned in product development" [21, p. 60].

Williamson defines simultaneous engineering as the process of "integrating all the functions responsible for bringing new products to market to reduce manufacturing costs and lead times whilst improving product quality and functionality" [21, p. 60]. The result is improved financial performance of the company. Thus, simultaneous engineering requires that functional and cost requirements of a product or products be matched against the limitations of available manufacturing processes. Product design and manufacturing decisions must concurrently be optimized to enable products of higher product performance and lower manufacturing costs.

Customer requirements and market considerations are often ignored during product and process design. For effective simultaneous engineering, management must bring together all of the different departments, including those that are focused on internal activities, as well as those which interface with external activities. Firms must strive to simultaneously design the product as well as the manufacturing process or facility, based on inputs from all required and relevant functions or specialties such as design, manufacturing and marketing. This would allow for product designs that are produceable, are delivered on time, and are within budget. Figure 1.1 illustrates the simultaneous engineering environment based on Williamson's definition and as it applies to this study.

1.2 The Design Dependent Parameter Approach

Design dependent parameters are defined by Fabrycky [4] as design characteristics inherent in the product or system that are subject to manipulation by the designer while seeking an optimal system design. The design dependent parameter approach is utilized in this research to evaluate candidate product and resource or facility design configurations. It is a methodology that permits indirect experimentation with the system being designed, in order to optimize system design. Indirect system experimentation for design optimization is made possible by the manipulation of a design evaluation function incorporating design dependent parameters.

The design dependent parameter approach utilizes a design evaluation function which mathematically links design actions with operational outcomes and allows system designers to determine the effect of alternative system characteristics on system performance. In most design situations, system performance is expressed by an economic evaluation measure. The evaluation measure used in this research is expected profit generated from implementing the candidate system. The design evaluation process from Fabrycky and Blanchard [5], illustrated in Figure 1.2, provides a framework in which the

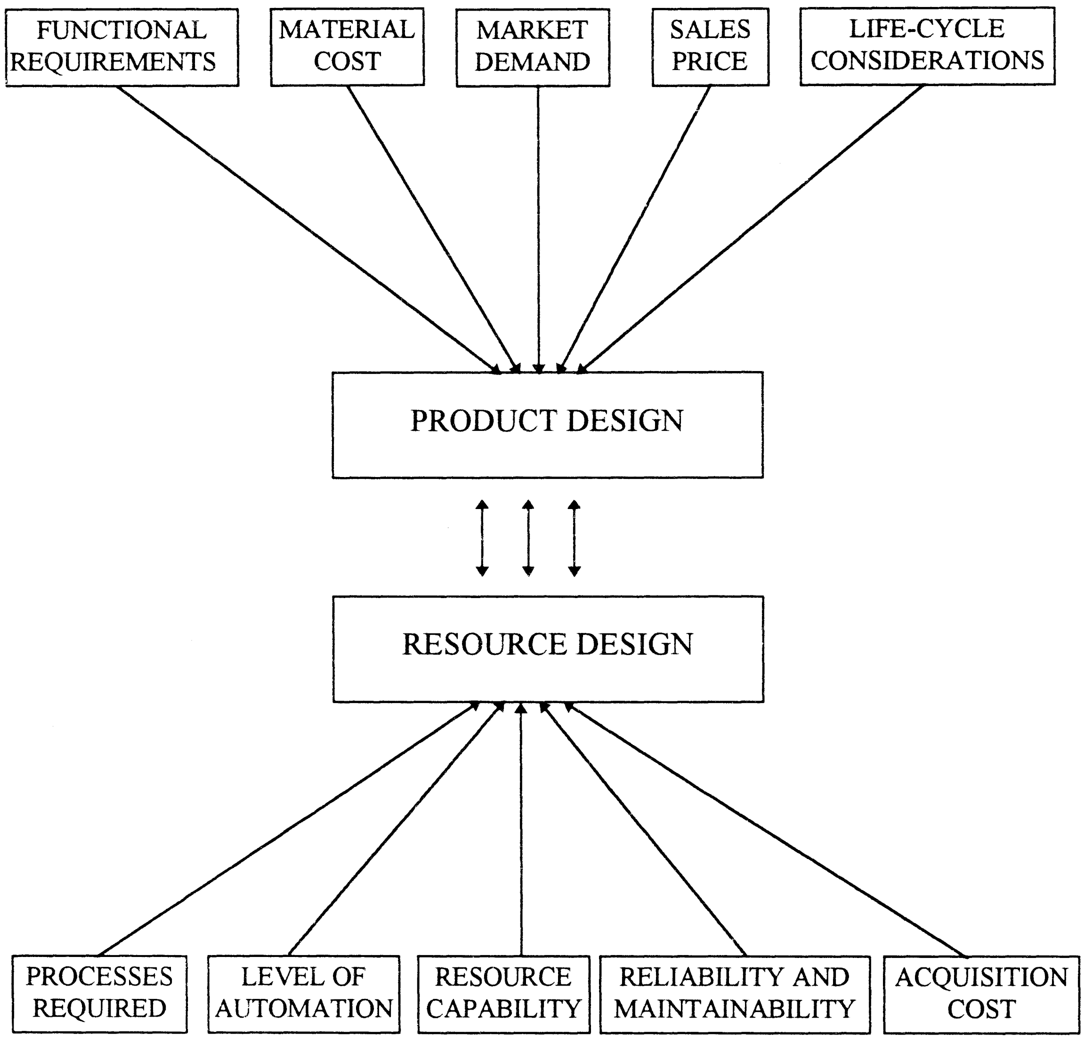

Figure 1.1 The Simultaneous Engineering Environment

mutually exclusive product or resource design alternatives generated during simultaneous engineering design activity can be evaluated and the most attractive design configuration selected for subsequent implementation. The design evaluation function used to evaluate alternative system design configurations, is expressed in Equations 1.1 and 1.2.

$$E = f(X, Y_d, Y_i) \tag{1.1}$$

$$\text{Subject to } g(X, Y_d) \overset{<}{\underset{>}{=}} C \tag{1.2}$$

Where:

E is an evaluation measure.

X is the set of design variables.

Y_d is the set of design dependent parameters.

Y_i is the set of design independent parameters.

C is the set of constraints.

To Optimally Achieve

ACQUISITION / UTILIZATION

Mathematically Link

DESIGN / OPERATIONS

Utilizing The

•DESIGN EVALUATION FUNCTION (DEF)•

For Choosing Among Design Alternatives

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

Subject to $g(X, Y_d) \overset{<}{\underset{>}{=}} C$

Figure 1.2 The Design Evaluation Process

1.3 Design Evaluation in Simultaneous Engineering

Simultaneous engineering design activity results in the generation of alternative candidate designs for both the product and the manufacturing resources. These candidate designs must be evaluated with a suitable economic evaluation function before a design configuration can be selected for implementation.

Existing simultaneous or concurrent engineering methodologies and tools are aimed at enhancing the quality of product designs and at reducing the design cycle time. Matin and Evans [12] have classified simultaneous engineering methods into the following categories:

1. Management based methods: These methods are concerned with development and implementation of corporate philosophies and encompass areas such as team working, project management, and the like.
2. Methods of geometric manipulation of drawings and models: These methods encompass the area of product design and, more specifically, computer aided design (CAD) techniques.
3. Formal methods: These methods cover the spectrum of techniques used to improve processes, such as quality function deployment (QFD), design for assembly and manufacture (DFA/M), and failure mode and effects analysis (FMEA).

There does not, at present, exist a methodology that permits simultaneous design evaluation for candidate design configurations using a singular economic objective such as expected profit. The simultaneous engineering process is impeded by the absence of such a methodology that can evaluate candidate product and resource (or facility) designs on the basis of profits resulting from the implementation of a particular product and resource design configuration. This research effort is aimed at developing such a methodology.

The design evaluation models developed for this thesis would enable the simultaneous engineering design evaluation of each candidate design configuration. A search of the feasible design space is enabled by using the design dependent parameter approach, in order to determine the configuration that results in the highest expected profit.

1.4 Research Objectives

The first objective of this research effort is to develop a single period design evaluation model that can be applied during simultaneous engineering design activity to evaluate alternative candidate product and resource (or facility) design configurations. The model developed in this thesis can be applied to situations where a simultaneous engineering design effort is necessitated in an existing manufacturing facility, or where a new manufacturing facility is being set up. Given the set of possible products being considered for production, and the set of resources required for producing these products, the model would help designers to determine: product designs to be implemented, the production quantities for each product, resource designs to be implemented, the number of units of each resource to be acquired, and the expected profits that would result for that design configuration. The model would enable design teams to evaluate candidate design configurations using the design evaluation function. The evaluation function will use a linear, mixed integer optimization based search to evaluate each candidate design configuration.

The second research objective is to develop an integrated, menu based, software application that implements the model using XPRESS-MP, a mathematical programming modeling language and optimizer, along with Paradox 3.5 for DOS, a relational database management system. Input data is entered, edited, manipulated and stored in Paradox tables and is read directly by the modeler before each optimization run. The interactive linkage between XPRESS-MP and Paradox makes data handling simple and efficient and provides for effective model implementation.

The third objective of this study is to demonstrate the applicability and use of the model in the design evaluation process. A hypothetical baseline design scenario is used to demonstrate the applicability of the design evaluation model. The effect of changing manufacturing resource reliability and maintainability on expected profit is investigated. Candidate design alternatives are evaluated using the design evaluation model to determine the design configuration that results in highest expected profit.

The final research objective is to extend the design evaluation model such that it can be applied to situations where the design space is constrained and where a complete, a priori, enumeration of all feasible design alternatives is possible. The extended constrained-design evaluation model is applicable to situations where design alternatives are considered to be mutually exclusive. The design evaluation methodology for the extended model does not utilize the design dependent parameter approach; it assumes the design space to be finite.

1.5 Research Limitation

Simultaneous engineering has been defined for the study as a business philosophy primarily aimed at reducing product time to market and enhancing product value and customer satisfaction. Simultaneous engineering requires integration and synchronization of all activities and functions responsible for bringing a product or products into being. It is the process of matching functional, cost and market requirements of products against the limitations of required manufacturing resources.

This research does not seek to model product time to market. Reduction in product time to market brought about by implementing simultaneous engineering philosophy is well documented in existing research. Such reductions in product time to market typically vary between 30% to 60% [Gatenby et all, 7].

This research deals with the subject area of design evaluation in a simultaneous engineering environment. The design evaluation models developed in the thesis enable concurrent evaluation of candidate product and manufacturing resource designs that are generated during simultaneous engineering design. These models evolve from simultaneous engineering philosophy in that they are used to match functional, cost and market requirements of products against the functional, cost and operational requirements of the required manufacturing resources over their respective life cycles.

1.6 Research Approach

This thesis is divided into the following sections: a survey of the available literature in the relevant subject areas, development of the design evaluation model, mathematical programming using a relational database management system, demonstration of the design evaluation methodology, and development of extended design evaluation model for the constrained-design scenario. Literature in the areas of simultaneous or concurrent engineering, aggregate production planning and capital budgeting, and implementation of mathematical programming models was reviewed as part of this research effort.

The findings of the literature search are presented in Chapter 2. In Chapter 3, the design variables and system parameters are identified, assumptions for the model are stated, and the simultaneous engineering design evaluation model is developed. Chapter 4 deals with the subject area of mathematical modeling using relational database theory. The interactive linkage of XPRESS-MP and Paradox, and its benefits, are explained. In addition, the Simultaneous Engineering Design Evaluation software application, SEDE 1.0, is developed in the chapter to implement the design evaluation model. Chapter

5 and Chapter 6 demonstrate the simultaneous engineering design evaluation methodology and the application of the design evaluation model developed in Chapter 3. In Chapter 5 a hypothetical baseline design configuration is defined and the effect of changing manufacturing resource reliability and maintainability on expected profit is investigated. In Chapter 6 alternative design scenarios are sequentially evaluated to determine the design alternative that results in the highest expected profit. In Chapter 7 an extended model applicable to the constrained-design scenario is developed and demonstrated. The thesis closes with conclusions and recommendations for further research in Chapter 8.

A user's guide for SEDE 1.0 as well as XPRESS-MP input files for the models developed in the study are included as appendices.

2.0 LITERATURE REVIEW

The literature surveyed and cited for this research falls under the categories of simultaneous or concurrent engineering, capital budgeting and aggregate production planning, and implementation of mathematical programming models. This chapter provides a discussion of the cited literature and its relevance to this thesis research.

2.1 Simultaneous Engineering

Relevant literature was sought and reviewed in the field of simultaneous engineering and concurrent engineering. These terms were found to be used interchangeably in the literature. The evolution of concurrent or simultaneous engineering practice can be traced as far back as World War II. Ziemke and Spann [23] trace the evolution of concurrent engineering or simultaneous engineering and list specific applications and accomplishments of its subsets, design for manufacture, and design for assembly.

Jo, Parsaei, and Sullivan [10] have identified team based approaches and computer based approaches as two basic approaches to implement concurrent engineering practice. The former approach is human oriented wherein teams consisting of designers and specialists from related functional areas. They suggest that the multi-functional team is essential for effective implementation and can quickly identify potential problems and undertake timely remedial action. In computer based approaches, the concurrent engineering philosophy is woven into the logic operations to enable design optimization over the life cycle. They suggest a direct relationship between technical and economic competitiveness and concurrent or simultaneous engineering practice by stating "concurrent engineering has a key role to play in the computer integrated manufacturing systems and the extent to which the concurrent engineering principles are applied will be the major deciding factor of the competitiveness of a nation's industries" (p. 18). However, their treatment of the simultaneous engineering process does not include the development of an economic optimization function that is used to optimize the design over the life cycle. The design evaluation methodology developed in this thesis falls under the category of computer based approaches and would enable effective comparison of design alternatives.

Noble [14] discusses the scope of the concurrent engineering problem as it relates to design and economic issues. He states the motivation for concurrent engineering as primarily economic and stresses the need to develop tools to integrate economic issues, such as management, marketing, finance, purchasing, accounting and suppliers, into the traditional areas of the concurrent engineering process, such as product design, process design, and manufacturing. Noble also differentiates between economic justification and economic design in that 'in economic justification the goal is to determine if a product or system meets the economic criteria for acceptance, hence justification. In economic design the goal is to consider economic issues as part of the design decision process. Therefore, a different approach must be taken with each to include economics in the design process" (p. 354). An integrated multi-objective economic product and process design approach, termed *design justification*, is presented by Noble [14] and Noble and Tanchoco [15]. It provides a framework for integrating both the product and process design from a combined economic and performance standpoint. The simultaneous engineering design evaluation methodology presented in this thesis differs from this work in that it evaluates product and process design alternatives against a single economic objective. In addition, the methodology assumes that all alternative designs for the products as well as the manufacturing resources posses the same functional characteristics.

2.2 Capital Budgeting and Aggregate Production Planning

The simultaneous engineering design evaluation model developed in this thesis is an extension of the aggregate capital budgeting model developed by Moolman [13].

Moolman addresses the problem of capital budgeting interactively with aggregate production planning and market supply and demand functions. Prior to further discussion, it would be beneficial to define the terms *capital budgeting* and *aggregate production planning*.

Capital budgeting is defined by Shim and Siegel [17, p. 81] as "the process of deciding whether or not to commit resources to a project whose benefits will spread over several time periods. There are typically two types of investments: Selection decisions in terms of obtaining new facilities or expanding existing facilities. Examples include: (a) Investments in long-term assets such as property , plant, and equipment. (b) Resource commitment in the form of new product development, market research...; and Replacement decisions in terms of replacing existing facilities... . As such, capital budgeting decisions are a key factor in the long term profitability of the firm. To make wise investment decisions, managers need tools at their disposal that will guide them in comparing the benefits and costs of various investment alternatives". The process of deciding which products to produce, the production quantity of each of these products, and the resource capacities to be acquired in the planning period or periods also falls under the purview of capital budgeting problems. Traditionally, capital budgeting problems assume a unique cash flow per project, by doing so allocating costs to the respective projects. See, for example Weingartner [18].

Aggregate production planning, on the other hand, is concerned with the determination of production, inventory, and work force levels to meet fluctuating demand requirements with the aim to minimize resource utilization costs. The resources are usually assumed to be fixed. Bedworth [1, p.121] defines the objective of aggregate planning as "the productive utilization of both human and equipment resources. The word *aggregate* means that all the planning is conducted at a gross level to meet the total demand from all products that share the same limited resources of a dedicated facility".

Capital budgeting is traditionally not modeled in an integrated fashion with aggregate production planning. However, Moolman [13, p. 238] suggests that "there exists a significant interface between capital budgeting and aggregate production planning. In fact, the only differences between these two activities are probably the objective and the level of detail of concern. Classically, capital budgeting is concerned with the selection of projects and the capital outlay required to complete the projects effectively... a top down approach. On the other hand, aggregate production planning is concerned with the effective utilization of resources... a bottoms-up approach. Capital budgeting and aggregate production planning can, therefore, be considered the two activities that cover the spectrum of production planning, where capital budgeting is at the top and aggregate production planning at the bottom". Moolman's model addresses the problem of capital budgeting interactively with aggregate production planning and market demand and supply functions.

The development of a model to evaluate alternative product and resource designs, generated during simultaneous engineering design activity, using expected profits as the evaluation measure would, as it's starting point, require capital budgeting to be modeled interactively with aggregate production planning and market functions. Thus Moolman's aggregate capital budgeting model [13, p.177], presented in Model I, is extended and used in this study for design evaluation.

The important features of his model, as they apply to this study, are listed below.

1. A product portfolio approach is employed and potentially produceable products are grouped in a portfolio.

2. Cash flows are not allocated to individual products. Cost is considered to be incurred in the acquisition and utilization of the resources. The utilization of resources is in the form of activities.
3. Demand is placed on the resources by the portfolio of products.
4. The primary objective of the model is profit maximization.

Model I

Maximize:

$$\sum_{p=1}^{4}\{S_p - \sum_{a=1}^{2} D_{pa}C_{pa}^{x} - MC_p^{x}\}X_p - \sum_{p=1}^{4} C_p^{y}Y_p - \sum_{r=1}^{2} C_r^{+}M_r^{+}$$

Subject to:

$$\sum_{p=1}^{4}\sum_{a=1}^{2} D_{pra}X_p - K_r^{+}M_r^{+} \le K_r^{0} \quad \forall r$$

$$X_p \le MD_p \quad \forall p$$

$$X_p - BM_pY_p \le 0 \quad \forall p$$

Where:

Decision variables:

X_p : Production quantity of product p

M_r^{+} : Number of units of resource r to acquire

Y_p : Product sustaining indicator ; 0 - 1 variable, 1 if product is produced

Parameters:

BM_p : A number just bigger than production quantity of product p

C_p^{y} : Product sustaining cost of product p

C_{pa}^{x} : Cost per unit consumption of D_{pa}

C_r^{+} : Acquisition cost per unit of M_r^{+}

D_{pra} : Amount of resource r consumed by activity a for product p

K_r^+ : Capacity per unit of resource r

K_r^0 : Initial capacity available for resource r

MC_p^x : Direct material cost per unit of product p

MD_p : Market demand for product p

S_p : Sales price per unit of product p

Subscripts:

a : Activity, with a maximum of A
p : Product, with a maximum of P
r : Resource, with a maximum of R

2.3 Implementation of Mathematical Programming Models

This research effort aims to develop a software application to implement the design evaluation model on a microcomputer. Literature was reviewed for the subject area of application and implementation of mathematical programming models for corporate planning. The findings of this literature search, relevant to this research, are presented in this section.

Mathematical programming and optimization analysis has been demonstrated to be a viable and effective tool at all corporate planning levels. However, its greatest usage has been at the tactical and operations planning level [Hirshfeld, 9]. Typical tactical and operations planning decisions include capital budgeting, aggregate production planning and production scheduling etc.. At these levels, planning involves the allocation of limited physical and capital resources across competing, interacting activities. Such allocation is precisely what mathematical programming does.

Based on readings from relevant literature, it can be stated that effective implementation of mathematical programming formulations is constrained by the following imperatives:

1. Difficulty in modeling: Difficulty in modeling most corporate decisions in terms of a linear mathematical model. Also, for most corporate decisions, it is difficult to determine a singular objective. Nonetheless, many models and approaches have been developed to aid decision making.
2. Data collection: Data collection is difficult and time consuming. The vast amounts of data provided by a corporate information database system is often inappropriate to what is at issue [Shapiro, 16]. Also, although there is no dearth of efficient solvers capable of handling very large problems, there are few systems that provide facilities to deal with the large amounts of data that go with a large mathematical model [Whitaker and Brown, 19].
3. Model size: The size of the optimization models, in terms of both variables and parameters, coupled with the difficulty in data handling described above, makes the implementation and use of standalone optimization models cumbersome and time consuming.
4. Non-stationary input parameters: Due to the short horizon of such planning models, the values of the input parameters can be very non-stationary. These parameters are, thus, subject to a high frequency of change based on changes in the day to day operations and business environment [Hirshfeld, 9]. For example, in seasonal businesses, operating plans must reflect seasonal variations in capacities, resource supplies, product demands, quality requirements, prices, and costs etc..
5. Interdependency of input parameters: Many input parameters of models are functions of other parameters and a change in the value of one related parameter can lead to changes in several others. This further contributes to the data handling problems.

Williams [20] discusses some practical considerations on the solution of mathematical programming models, the use of computers and algorithms and software packages available for the purpose. He demonstrates the use of XPRESS-MP, the modeling language and solver used to implement the design evaluation models developed in this study.

Fourer [6] specifically compares *modeling languages* and *matrix generators* for the purpose of linear programming. Prior to further discussion, it would be beneficial to define both modeling languages and matrix generators.

Williams [20, p. 39] defines matrix generators as "software aids for helping the user to structure and input his problem into a package in the form of a model". Fourer [6, p. 155] defines a modeling language as a software tool that makes it possible to "... express any linear program in modeler's form..." as input to a computer system. A modeling language must thus satisfy two opposing requirements:

1. It should be as similar as possible to conventional model writing or to a model written in the modeler's form.
2. Its syntax and semantics must be unambiguous and lucid such that it can be efficiently processed and translated by computer systems.

Both, matrix generators and modeling languages have obvious advantages since most models are so large that the manual preparation of data for input to a linear programming package is highly tedious and error prone. Also, as stated earlier, most models also involve related and repetitious data. However, Fourer also lists some general drawbacks of matrix generators and specific drawbacks of currently available generators and also compares the advantages of both matrix generators and modeling languages. It is ultimately argued that modeling languages are more reliable and can lead to lower overall costs for linear programming applications. An important issue that Fourer fails to address in his discussion of modeling languages and matrix generators is the inability of the discussed modeling languages to read data directly from external data sources such as spreadsheets and databases. Most modeling languages and matrix generators are capable of importing data from data files, but it must be understood that these data files are not the naturally occurring source of data in the corporate world, but have to be created from data elements derived from the corporate information system database. Creation of such data files is both tedious and error prone. XPRESS-MP, the modeling language and linear mixed-integer solver, used to implement the design evaluation model permits data to be imported directly from database tables at the time of matrix generation.

Whitaker and Brown [19] discuss the use of a relational database management system for preparing and editing large amounts of data for a linear programming system for a company. They have determined the combination of the linear programming optimizer and the relational database management software to be a user friendly system on a micro-computer that makes implementation of the large linear programming model easy and effective. They hypothesize an ideal linear programming modeling system as a "database system that operates like its spreadsheet equivalent, where at the press of a function key the system solves the defined model and the optimum solution appears in the database" and which "can generally be applied to any optimization system where the optimizer is making use of large amounts of data" (p. 39). The simultaneous engineering design evaluation application developed in the thesis is based on the these recommendations made by Whitaker and Brown.

3.0 SIMULTANEOUS ENGINEERING DESIGN EVALUATION MODEL

In this chapter, the simultaneous engineering design evaluation model is developed and presented. The model permits evaluation of candidate design configurations, comprising product and manufacturing resource designs, generated during simultaneous engineering design activity. Candidate design configurations are generated on account of identification of alternative product and resource designs. The evaluation measure is expected profit resulting from the implementation of the design configuration under consideration.

3.1 Design Variables and System Parameters

Prior to defining the design variables and system parameters, it would be beneficial to define the system being designed. The system comprises a manufacturing facility considering to manufacture some or all products from a set of 'P' possible products. All the products require a maximum of 'R' resources to be manufactured. The system design variables (X) describing the state of the system can now be identified as:

X_p, the production quantity of product p

M_r, the number of units of resource r to be acquired

The design dependent parameters (Y_d) of the system are:

CRC_r, the periodic equivalent resource cost per unit for resource r

D_{pr}, the amount of resource r consumed by a unit of product p

M_{pt}, the mean preventive maintenance time for resource r

M_{ct}, the mean corrective maintenance time for resource r

MC_p, the direct material cost per unit of product p

λ_r, the failure rate for resource r

The design independent parameters (Y_i) of the system are:

C_p, the product sustaining cost for product p

C_{pr}, the unit consumption cost for each unit of resource r

fpt_r, the preventive maintenance rate for resource r

IK_r, the installed capacity for each resource r

MD_p, the market demand for product p

S_p, the sales price for product p

3.2 Development of the Design Evaluation Model

In this section, the simultaneous engineering design evaluation model is developed. This model is applicable to scenarios where a new manufacturing facility is being set up and is currently in the process of simultaneous engineering design, or where a simultaneous engineering design effort is necessitated at an existing manufacturing facility. As stated, the design evaluation model is an extension of Model I which models capital budgeting interactively with aggregate production planning. Model I provides the basic framework by which profits are maximized given the products and resources. However, it only addresses the acquisition phase of the life cycle of resources and does not explicitly model the parameters associated with the utilization phase of the resource life cycle.

Simultaneous or concurrent engineering, by definition, is life-cycle complete and thus simultaneous or concurrent engineering methodologies require consideration of all phases of the life cycle for both the products as well as the manufacturing resources. However, it is assumed that the products being considered for production are consumable. Accordingly, the utilization phase of the product life cycle is ignored. The developed model explicitly includes design dependent and design independent parameters associated with the utilization phase of the manufacturing resource life cycle. These parameters are the failure rate of manufacturing resources, preventive maintenance rate of resources, mean preventive maintenance time for resources, and mean corrective maintenance time for resources. To ease modeling, these parameters can be reduced to the single design dependent parameter, achieved availability.

Blanchard and Fabrycky [5, p.359], define achieved availability (A_a) as "the probability that a system or equipment, when used under stated conditions in an ideal support environment (i.e. readily available tools, spares, personnel, etc..), will operate satisfactorily at any point in time". Achieved availability is similar to operational availability but excludes logistic and administrative delay times. It assumes that these delays do not occur. Additionally, logistic and administrative delay times can be difficult to determine ahead of facility implementation. Achieved availability can be expressed mathematically as in Equation 3.1.

$$A_a = MTBM \, / \, (MTBM + \overline{M}) \qquad (3.1)$$

Where:

$\overline{M}$ is the mean active maintenance time, measured in hours

MTBM is the mean time between maintenance, measured in hours

Also,

$$MTBM = 1 \, / \, (\lambda + fpt) \qquad (3.2)$$

Where:

fpt is the preventive maintenance rate, measured as number of preventive maintenance actions per year

λ is the failure rate, measured as number of failures per year

Also,

$$\overline{M} = \{ (\lambda \, . \, M_{ct}) + (fpt \, . \, M_{pt}) \} \, / \, (\lambda + fpt) \qquad (3.3)$$

Where:

M_{ct} is the mean corrective maintenance time measured in hours

M_{pt} is the mean preventive maintenance time measured in hours

Substituting Equations 3.2 and 3.3 into Equation 3.1 and solving, we obtain,

$$A_a = 1 \, / \, \{ 1 + (\lambda \, . \, M_{ct}) + (fpt \, . \, M_{pt}) \} \qquad (3.4)$$

Also,

$$AK_r = A_a \, . \, IK_r \qquad (3.5)$$

Where:

AK_r is the available capacity for resource r

IK_r is the installed capacity for resource r

Also,

$$CRC_r = (P - F)(A / P, i, n) + F(i) + \{ \sum_n M_n (P / F, i, n) \}(A / P, I, n) \quad (3.6)$$

Where:

CRC_r is the periodic equivalent resource cost per unit for resource r

F is the salvage value of resource r, if any

M_n is the resource maintenance cost in the n'th year

P is the first cost or acquisition cost of resource r

(A / P, i, n) is the capital recovery factor

(P / F, i, n) is the present amount factor

Also,

$$(A / P, i, n) = 1 / (1 + i)^n \quad (3.7)$$

and $$(P / F, i, n) = \{ i . (1 + i)^n \} / \{ (1 + i)^n - 1 \} \quad (3.8)$$

Where:

i is the interest rate used for discounting future cash flows

n is the time period

The design evaluation model can now be stated as Model II.

Model II

Maximize:

$$\sum_{p=1}^{P}\{S_p - \sum_{r=1}^{R} D_{pr}C_{pr} - MC_p\}X_p - \sum_{p=1}^{P} C_p Y_p - \sum_{r=1}^{R} CRC_r M_r$$

Subject to:

$$\sum_{p=1}^{P} D_{pr}X_p - AK_r M_r \leq 0 \quad \forall r$$

$$X_p \leq MD_p \quad \forall p$$

$$X_p - BM_p Y_p \leq 0 \quad \forall p$$

Where:

Decision variables:

X_p : Production quantity of product p

M_r : Number of units of resource r to acquire

Y_p : Product sustaining indicator; 0 - 1 variable, 1 if product is produced

Parameters:

BM_p : A number just bigger than production quantity of product p

C_p : Product sustaining cost of product p

C_{pr} : Cost per unit consumption of D_{pr}

CRC_r : Periodic equivalent resource cost per unit of M_r

D_{pr} : Amount of resource r consumed by product p

AK_r : Available capacity per unit of resource r

MC_p : Direct material cost per unit of product p

MD_p : Market demand for product p

S_p : Sales price per unit of product p

Subscripts:

a : Activity, with a maximum of A

p : Product, with a maximum of P

r : Resource, with a maximum of R

Given the set of possible products being considered for production, the set of resources required for producing these products, resource consumption data and material cost for the products, and resource data such as acquisition cost, installed capacity, maintainability and reliability of resources, the design evaluation model would help determine production quantities for each product and the number of units of each resource to be acquired. The design evaluation function, discussed in Section 1.2, would make use of this design evaluation model to evaluate each alternative design configuration in the finite feasible design space.

3.3 Assumptions of the Model

The design evaluation model, Model II, is limited by the following set of assumptions:

1. The model is a linear mixed integer formulation and the inherent assumptions of linear programming are acceptable.
2. The model is not a multi-period model and refers to a single planning period. This planning period is defined for the study as the duration of time for which the input parameters of the model do not change significantly.
3. The model does not distinguish between activities and resources, as is the case for Model I. Costs are assumed to be incurred in the acquisition of resources as well as the utilization of resources.
4. The model assumes that the products being considered for production are consumable and are not repairable or maintainable.

5. It is assumed that each of the ‘P’ products require a maximum of ‘R’ manufacturing resources.
6. The model does not consider the sequence or routing of the production processes or resources. Hence, delay times and time spent in queues is ignored.
7. The model uses periodic equivalent resource cost for production resources as opposed to first or acquisition cost. The periodic equivalent cost is the same for all subsequent periods and takes into consideration the first cost, maintenance cost, and the salvage value, if any, of the production resources over their life cycle. The determination of the appropriate interest rate for discounting future cash flows to determine the periodic equivalent resource cost is assumed beyond the scope of this thesis.
8. The mean time between failure of resources is assumed to remain constant. Reliability of resources is, thus, assumed to be insensitive to the age of resources.
9. Administrative and logistic delay times for resource maintenance are assumed to be zero and are not modeled.
10. Functional characteristics of the products are assumed to be the same when they are redesigned. Hence market demand and sales price of the products are assumed to remain unchanged.
11. If and when resources are redesigned, it is assumed that the redesigned resources identically duplicate the production process.
12. The unit consumption cost for the resources is assumed to be independent of the products processed on that resource.
13. XPRESS-MP, the modeling language and solver used to implement the model is assumed to incorporate all sufficient and necessary conditions for optimality.

4.0 DESIGN EVALUATION USING XPRESS-MP AND PARADOX

The simultaneous engineering design evaluation model developed in the previous chapter is implemented using XPRESS-MP, a linear mixed integer modeling language and solver, and Paradox 3.5 for DOS, a relational database management system software package. An integrated, menu driven application, called SEDE 1.0, is developed for this purpose. This application provides for effective use, demonstration, and possible implementation of the design evaluation model. In this chapter, the interactive linkage of XPRESS-MP with Paradox is discussed and the microcomputer based application is presented.

4.1 Interactive Linkage of XPRESS-MP with Paradox

Input data for the model is manipulated using Paradox. Paradox, as would any relational database management system, permits the user to store data values as a relation of other data elements stored in the same or other tables. It automatically updates all related data elements whenever a data element is changed or updated. Data values for model input parameters are entered, edited and stored in four tables created using Paradox, namely Table 1 through Table 4.

Table 1 is used for product related data and contains the following data fields: sales price (S_p), market demand (MD_p), product sustaining cost (CP_p), and material cost per unit (MC_p). Table 2 contains resource consumption data (D_{pr}). Table 3 is used to store resource related data in three data fields: periodic equivalent resource cost (CRC_r), unit consumption cost (C_{pr}), and installed capacity (Ik_r). Finally, Table 4 is used to store resource maintainability and reliability data and includes the data fields: failure rate (λ), preventive maintenance rate (fpt), mean preventive maintenance time (M_{pt}), and mean corrective maintenance time (M_{ct}).

XPRESS-MP is the modeling language and integer programming solver used to generate optimal values for the model decision variables. It consists of two main modules: MP-MODEL (modeling module), and MP-OPT (optimization module). MP-MODEL is used to define the model, import data for the input parameters from Paradox Tables 1 through 4 and to generate the matrix file that is read by MP-OPT. MP-OPT is used to read the input matrix file and generate an optimal integer solution using the branch and bound search technique. MP-OPT allows the user to modify the integer search procedure based on the problem so as to reduce problem solution time.

The interactive linkage of XPRESS-MP with Paradox is depicted in Figure 4.1. The primary problem is to permit direct data exchange between Paradox tables and the design evaluation model defined using MP-MODEL, the modeling module of XPRESS-MP. The flow diagram for the proposed application, SEDE 1.0, is illustrated in Figure 4.2.

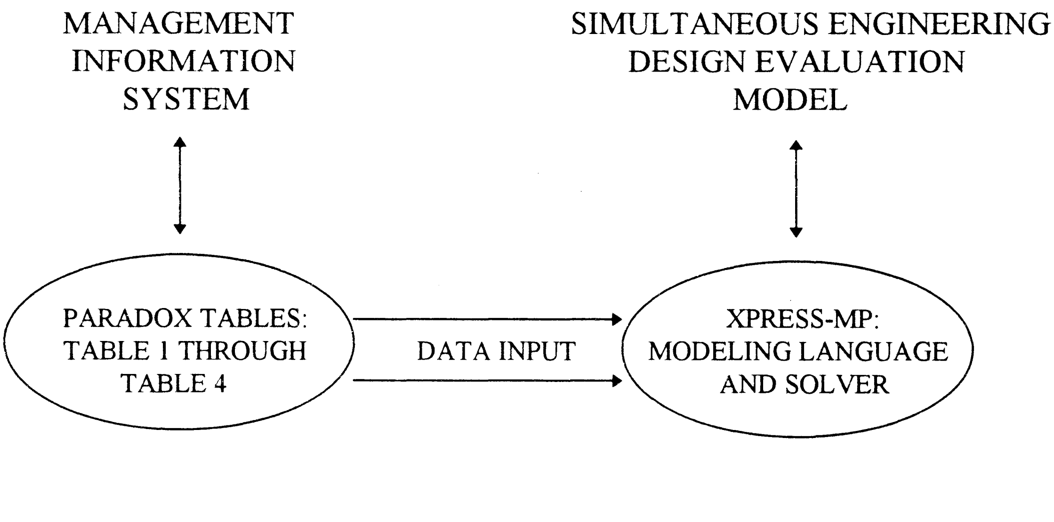

Figure 4.1 Interactive Linkage of XPRESS-MP with Paradox

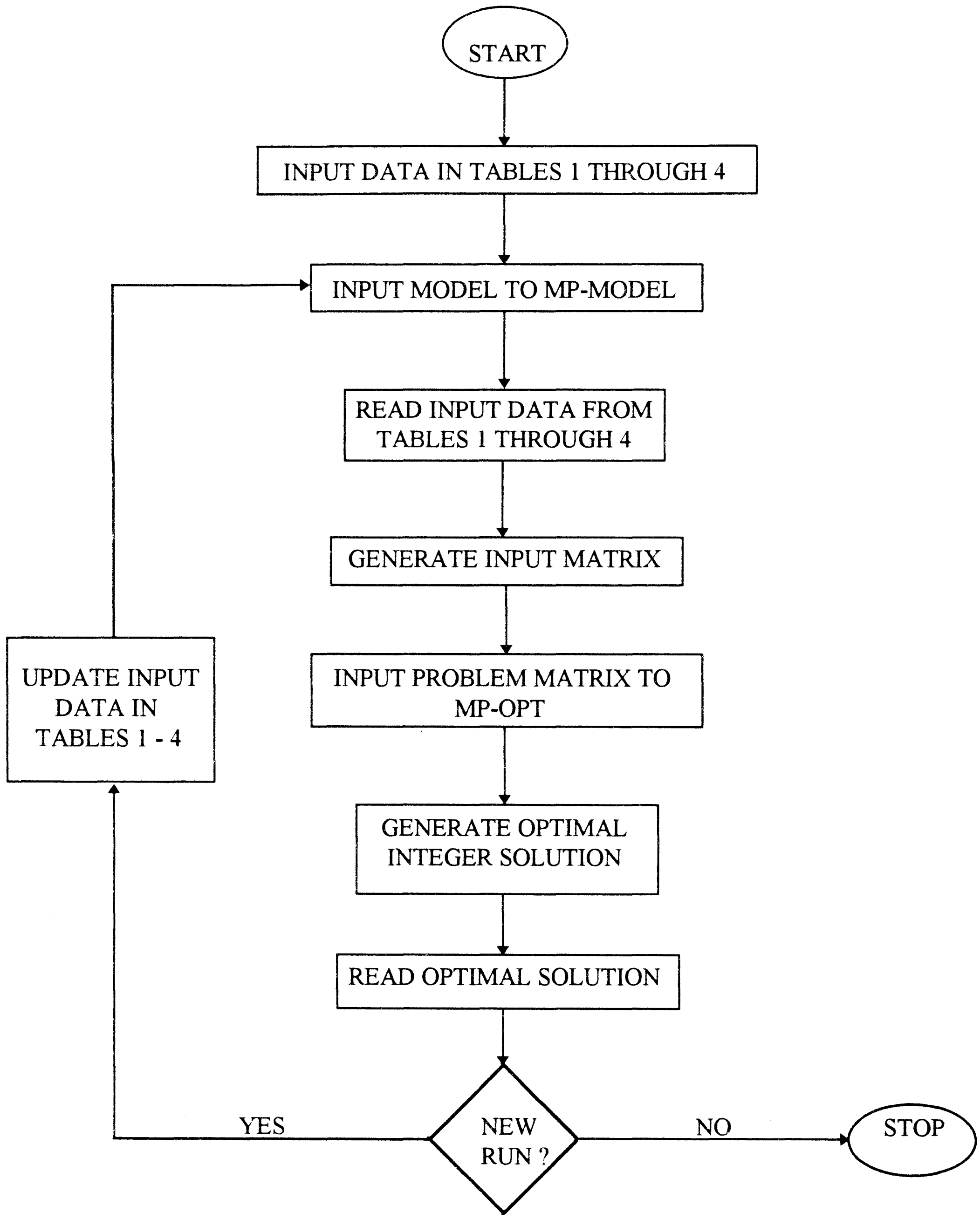

Figure 4.2 Flow Diagram for SEDE 1.0

4.2 Benefits of the Interactive Linkage

The interactive linkage makes the use and implementation of the design evaluation model user friendly. Data handling is simplified and multiple runs of the model are made easy. To conduct a run, the user needs to update data in Tables 1 through 4 and, upon completion of the optimization, read the results generated by XPRESS-MP. The user is not required to edit the model files to run the model with changed input data. Other benefits are as listed below:

1. The input tables, in a real world situation, would belong to a larger relational database management system underlying a management information system in place within an organization. The data elements in these tables could be relations of one or several other data elements belonging to other data tables of the database. If changes were made to the data elements in any of these tables belonging to the database, the relevant data elements in Tables 1 through 4, would be immediately updated. Hence, updated data for the model parameters is readily available and data collection is simplified.
2. Many input parameters of the models are functions of either one or several other data elements contained in Tables 1 through 4. Although the design evaluation application, developed in Section 4.3, uses MP-MODEL to compute the values for these input parameters, in a larger life-sized model it would be easier to create a set of related tables that automatically compute and store the values for all input parameters for the models. In such case, the input parameters can be read directly from the relevant Paradox tables requiring no further computations.

The primary advantage offered by this interactive linkage is the relative ease of data handling. As discussed in Section 2.3, data handling difficulties arising due to model size, non-stationarity of input parameter values, and interdependence of input parameters remain the biggest impediment to effective usage and implementation of mathematical programming models. This combination of the linear programming optimizer and the relational database management software makes model implementation easy and effective.

4.3 Simultaneous Engineering Design Evaluation Software Application

The simultaneous engineering design evaluation software application, designated SEDE 1.0, is designed as a demonstration tool for educational purposes, to demonstrate the design evaluation model developed in Chapter 3. The application effectively incorporates the interactive linkage of XPRESS-MP and Paradox. The menu option screen displayed at the start of the application is presented in Figure 4.3.

SEDE 1.0 limits the design evaluation model to a maximum of six products requiring a maximum of six manufacturing resources. The production quantities for the six products under consideration are modeled as partial integer variables. The production quantities take integral values for values below thirty units. For values greater than thirty units, production quantities are allowed to take continuous values. This is necessitated due to the inability of XPRESS-MP to handle large integer values for model decision variables.

SIMULTANEOUS ENGINEERING DESIGN EVALUATION

1. EDIT INPUT DATA IN PARADOX TABLES
2. GENERATE INPUT MATRIX
3. GENERATE OPTIMAL INTEGER SOLUTION
4. READ RESULTS
5. QUIT

Type the number you want and press ENTER:

Figure 4.3 SEDE 1.0 Menu Option Screen

By choosing menu choice '1', Paradox is executed. The user can then input, manipulate, or update data values for model parameters in one or more input tables. Menu option '2' directs MP-MODEL, the matrix generator, to read updated input data from the data tables and generate the matrix file, SEDE.MAT. Menu option '3' directs MP-OPT, the solver, to search for an optimal integer solution using the matrix file SEDE.MAT. The optimal results are stored in an ASCII text file called SEDE.PRT. Menu choice '4' permits the user to read and print, if desired, the output file SEDE.PRT. Menu choice '5' allows the user to quit the application and return to DOS. A user's guide for SEDE 1.0 is attached as Appendix C.

5.0 EVALUATION OF A BASELINE DESIGN

This chapter, along with Chapter 6, presents a demonstration of the simultaneous engineering design evaluation methodology and the application of the design evaluation model, Model II, developed in Chapter 3. In this chapter, a hypothetical baseline design is presented and evaluated using Model II. The baseline design comprises initial product and manufacturing resource designs and is the starting point of the simultaneous engineering design effort. The baseline design is defined and evaluated in the first section. The second section focuses on determining the change in expected profit resulting from changes in resource reliability and maintainability for all resources under consideration in the baseline design. This analysis is of significant value as a precursor to simultaneous design of manufacturing resources and products and can provide resource designers (or manufacturing engineers) a direction in which to focus simultaneous design efforts for the manufacturing resources.

5.1 The Baseline Design

As stated in Chapter 3.0, the design evaluation model is applicable to both new manufacturing facilities as well as existing manufacturing facilities. The baseline design presented here is a manufacturing facility configured to manufacture consumable products. It is assumed that a maximum of six products are being considered for production and these products require a maximum of six manufacturing resources. The primary questions faced by the firm at this stage are determining the optimal expected profit resulting from the baseline design configuration, determining the optimal production quantities for the products, and determining the optimal number of resource units to be acquired for each resource type. The design dependent and the design independent parameter values for the baseline design are defined in Tables 5.1 through 5.4.

Table 5.1 Product Related Data for the Baseline Design

Products	Sales Price (S_p) Dollars/Unit	Market Demand (MD_p) Units	Product Sustaining Cost (C_p) Dollars	Material Cost (MC_p) Dollars/Unit
X1	120	1000	10,000	6.00
X2	150	5000	10,000	7.00
X3	135	3500	10,000	6.50
X4	180	2000	10,000	10.00
X5	95	5000	10,000	7.00
X6	175	1500	10,000	15.00

Table 5.2 Resource Consumption Data (D_{pr} in Hours/Unit) for the Baseline Design

Products	X1	X2	X3	X4	X5	X6
Resource M1	0.50	1.00	0.40	0.00	1.50	2.00
Resource M2	0.60	1.30	0.30	1.80	1.50	2.30
Resource M3	0.00	0.70	2.00	0.60	0.90	0.10
Resource M4	0.90	0.90	2.70	0.75	1.10	1.15
Resource M5	0.30	0.00	0.00	0.20	0.70	0.00
Resource M6	0.35	0.70	0.60	0.30	0.00	0.35

Table 5.3 Resource Related Data for the Baseline Design

Resources	Periodic Equivalent Resource Cost (CRC_r) Dollars	Unit Consumption Cost (C_{pr}) Dollars/Hour	Installed Capacity (IK_r) Hours/Year
Resource M1	30,000	7.50	8760
Resource M2	40,000	7.00	8760
Resource M3	75,000	10.00	8760
Resource M4	95,000	11.75	8760
Resource M5	100,000	9.00	8760
Resource M6	65,000	10.25	8760

Table 5.4 Reliability and Maintainability Data for the Baseline Design

Resources	Failure Rate (λ) Failures/Year	Preventive Maintenance Rate (fpt) Times/Year	Mean Preventive Maintenance Time (M_{pt}) Hours	Mean Corrective Maintenance Time (M_{ct}) Hours
Resource M1	5	4	1	5
Resource M2	8	4	1	8
Resource M3	2	4	3	9
Resource M4	3	4	3.5	12
Resource M5	3	4	5	13
Resource M6	4	4	6.5	18

The baseline design was evaluated using SEDE 1.0 and the expected profit resulting from it's implementation is determined to be \$634,887. SEDE 1.0 also determines the optimal production quantities for the set of products as well as the number of units of each resource to be acquired. The results obtained from SEDE 1.0 are presented in Table 5.5.

Table 5.5 Expected Profit and Optimal Values for Decision Variables for the Baseline Design

Expected Profit and Decision Variables	Optimal Value
Expected profit	\$ 634,887
Production quantity for Product X1	1000 Units
Production quantity for Product X2	5000 Units
Production quantity for Product X3	3500 Units
Production quantity for Product X4	2000 Units
Production quantity for Product X5	5000 Units
Production quantity for Product X6	1500 Units
Number of units of Resource M1 to be acquired	2 Units
Number of units of Resource M2 to be acquired	3 Units
Number of units of Resource M3 to be acquired	2 Units
Number of units of Resource M4 to be acquired	3 Units
Number of units of Resource M5 to be acquired	1 Unit
Number of units of Resource M6 to be acquired	1 Unit

5.2 Effect of Manufacturing Resource Reliability and Maintainability

This section addresses the change in expected profit resulting from changes in manufacturing resource reliability and maintainability for the baseline design. The design dependent parameter approach permits indirect experimentation with the system being designed. Indirect system experimentation is made possible by manipulation of design dependent parameter values. The system under consideration in this study comprises both, manufacturing resources and products, that are being simultaneously designed. However, at this stage, prior to simultaneous design of manufacturing resources and products, the study is concerned with obtaining a direction for optimizing design of manufacturing resources.

The manufacturing resource design dependent parameters of interest at this stage are: periodic equivalent resource cost of resource r (CRC_r), failure rate of resource r (λ), and mean corrective maintenance time for resource r (M_{ct}). The effect of varying manufacturing resource reliability and maintainability on expected profits can be determined using SEDE 1.0. Indirect experimentation with these design dependent parameters will identify values for manufacturing resource reliability and maintainability that result in higher expected profits and can provide a direction in which to focus subsequent simultaneous engineering design efforts.

Prior to determining the effect of manufacturing resource reliability and maintainability on expected profit, it is necessary to hypothesize the relationship between resource failure rate, resource mean corrective maintenance time (or mean time to repair), and periodic equivalent resource cost. As is illustrated in Figure 5.1, it is assumed that resource acquisition cost (or resource first cost) generally decreases exponentially, at a decreasing rate, with increasing failure rate and increases exponentially, at an increasing rate, with decreasing mean corrective maintenance time. Although this relationship varies for each type of manufacturing resource under consideration, for the sake of simplicity this study assumes that it is similar for all resources under consideration in the baseline design configuration.

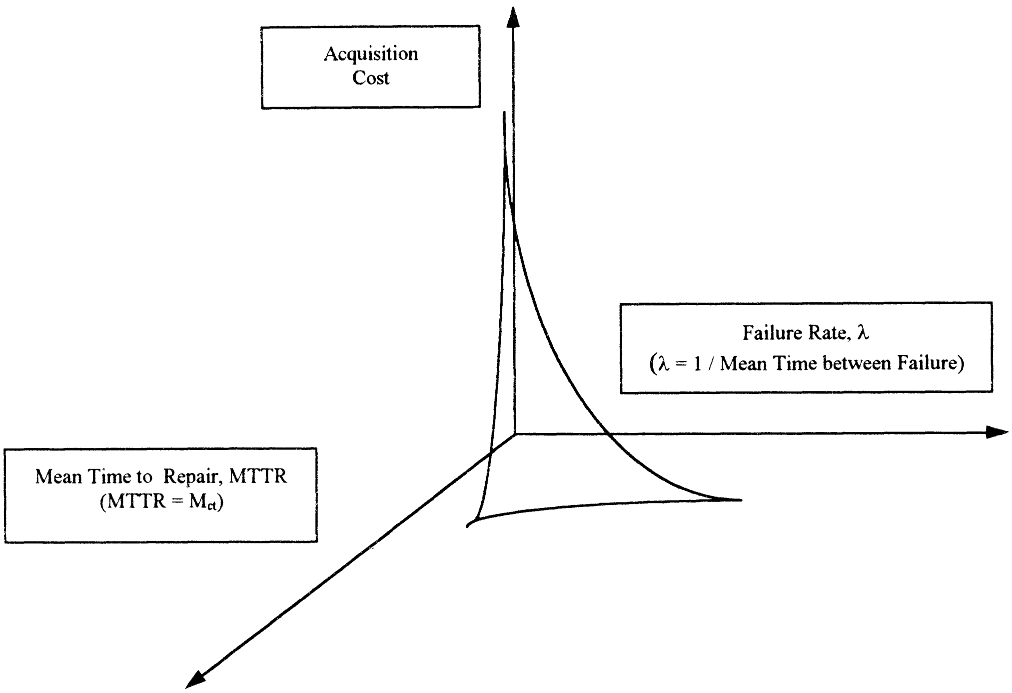

Figure 5.1 General Relationship between Resource Acquisition Cost, Failure Rate, and Mean Corrective Maintenance Time

Table 5.6 defines the relationship between periodic equivalent resource cost, resource failure rate, and resource mean corrective maintenance time for the manufacturing resources under consideration in the baseline design configuration. In the table, the parameter values are expressed as percentages, wherein 100 % corresponds to the value in the baseline design configuration. The percentage values in the body of the table are values for periodic equivalent resource cost.

Table 5.6 Assumed Relationship Between Periodic Equivalent Resource Cost, Failure Rate, and Mean Corrective Maintenance Time for the Baseline Design

Failure	Mean Corrective Maintenance Time (M_{ct})				
Rate (λ)	80 %	90 %	100 %	110 %	120 %
80 %	120 %	117 %	115 %	109 %	103 %
90 %	110 %	108 %	106 %	102 %	98 %
100 %	103 %	102 %	100 %	98 %	96 %
110 %	101 %	100 %	94 %	91 %	90 %
120%	100 %	98 %	92 %	86 %	80 %

The effect of varying resource reliability and resource maintainability together, for all resources being considered in the baseline design, is determined using SEDE 1.0. Results of this analysis are presented in Table 5.7. Again, values for failure rate and mean corrective maintenance time are expressed as percentages wherein 100 % refers to the respective data values in the baseline design configuration. All other input parameter data values for the design evaluation model are unchanged and correspond to the baseline design configuration. Additionally, the values in the body of the table are values for expected profit, corresponding to the resource reliability and maintainability parameter values.

The results presented in Table 5.7 indicate that expected profit would increase as resources are designed to be less reliable and less maintainable, assuming that product designs are unchanged and correspond to those presented in Tables 5.1 and 5.2. It is intuitively clear that diminishing returns would set in at a point beyond which a further reduction in manufacturing resource reliability and/or maintainability would result in reduced expected profit. However, the results presented in Table 5.7 do not exhibit diminishing returns in the range over which manufacturing resource reliability and maintainability was evaluated.

Table 5.7 Relationship Between Expected Profit, Failure Rate, and Mean Corrective Maintenance Time for the Baseline Design

Failure	Mean Corrective Maintenance Time (M_{ct})				
Rate (λ)	80 %	90 %	100 %	110 %	120 %
80 %	\$ 478,887	\$ 502,287	\$ 517,887	\$ 564,687	\$ 611,487
90 %	\$ 556,887	\$ 572,487	\$ 588,087	\$ 619,287	\$ 650,487
100 %	\$ 611,487	\$ 619,287	\$ 634,887	\$ 650,487	\$ 666,087
110 %	\$ 627,087	\$ 634,887	\$ 681,687	\$ 705,087	\$ 712,887
120%	\$ 634,887	\$ 650,487	\$ 697,287	\$ 744,087	\$ 790,887

This analysis is intended to precede simultaneous engineering design of manufacturing resources and products. It should be stated that all reliability and maintainability values presented and evaluated in Tables 5.6 and 5.7 may not be feasible manufacturing resource design alternatives. During simultaneous design activity, resource designers may seek to identify feasible manufacturing resource design alternatives within the regions that result in higher expected profit.

6.0 EVALUATION OF DESIGN ALTERNATIVES

The results obtained in Chapter 5 are significant value in that they provide a starting point for simultaneous engineering design. Simultaneous engineering design activity results in the identification of alternative designs comprising candidate manufacturing resource and product designs. Alternative designs must be evaluated using the design evaluation function to determine the design alternatives that results in highest expected profit. In this chapter design alternatives are identified and evaluated using Model II. Five design alternatives are identified and evaluated in this chapter. For each design alternative, SEDE 1.0 determines the expected profit resulting from the design alternative as well as the optimal values for the two sets of decision variables, production quantities of products and the number of units of resources to be acquired. Thus, the design alternative that maximizes expected profit can be selected for subsequent implementation.

6.1 Design Alternative I

In this design alternative, assume that Product X2 is redesigned such that each unit produced utilizes more processing time on both, Resource M1 and Resource M2. Also it is assumed that processing time on Resource M6 is not required to produce Product X2. It is also assumed that the material cost per unit of Product X2 is reduced. In addition, Resource M1 is redesigned to be more reliable and less maintainable. All other input parameter values are assumed to be unchanged and correspond to the respective values in the baseline design. The changed values for the design dependent parameters, together with the results obtained from SEDE 1.0, for this alternative are presented in Table 6.1.

The results presented in Table 6.1 indicate that expected profit from this design alternative is $600,137. This is less than the expected profit resulting from the baseline design (\$634,887). The manufacturing resource and product design changes proposed in this design alternative are no longer considered. For the second design alternative, the design of Product X2 and Resource M1 remains unchanged and corresponds to the baseline design. However, Product X3 and Resource M3 are assumed redesigned.

6.2 Design Alternative II

In this design alternative, Product X3 is redesigned such that each unit of the product requires less processing on Resource M4 but more processing time on Resource M1. In addition, it is assumed that Product X4 does not require processing on Resource M5. Resource M3 is assumed to be made more reliable and less maintainable. It is assumed that the acquisition cost for Resource M3 changes to correspond to changes in it's reliability and maintainability. Consequently, the periodic equivalent resource cost per unit of resource for Resource M3 also changes. All other model input parameters are assumed to be unchanged and correspond to the respective values in the baseline design configuration. The changed values for the design dependent parameters, together with the results obtained from SEDE 1.0 for this alternative are presented in Table 6.2.

The results presented in Table 6.2 indicate that expected profit from Design Alternative II is \$635,314. This represents an improvement over the expected profit resulting from the baseline design (\$634,887), but only marginally. The candidate designs for Product X3 and Resource M3 proposed in this design alternative do not substantially increase expected profits and are dropped from further consideration. Instead, for the third design alternative candidate designs for Product X6 and Resource M5 are evaluated using SEDE 1.0. The design of Product X3 and Resource M3 remains unchanged and corresponds to the baseline design.

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Table 6.2 Design Alternative II

Design Dependent Parameters, Expected Profit, and Decision Variables	Value
Amount of Resource M1 consumed by a unit of Product X3 (D_{X3M1})	0.55 Hours/Unit
Amount of Resource M4 consumed by a unit of Product X3 (D_{X3M4})	2.30 Hours/Unit
Failure rate (λ) for Resource M3	1.7 Failures/Year
Mean corrective maintenance time (M_{ct}) for Resource M3	11 Hours
Periodic equivalent resource cost per unit for Resource M3	$ 73,500
Expected profit	$ 635,314
Production quantity for Product X1	1000 Units
Production quantity for Product X2	5000 Units
Production quantity for Product X3	3500 Units
Production quantity for Product X4	2000 Units
Production quantity for Product X5	4691 Units
Production quantity for Product X6	1500 Units
Number of units of Resource M1 to be acquired	2 Units
Number of units of Resource M2 to be acquired	3 Units
Number of units of Resource M3 to be acquired	2 Units
Number of units of Resource M4 to be acquired	3 Units
Number of units of Resource M5 to be acquired	1 Unit
Number of units of Resource M6 to be acquired	1 Unit

6.3 Design Alternative III

As stated earlier, candidate designs for Product X6 and Resource M5 are evaluated in this design alternative. It is assumed that Product X6 is redesigned to reduce it's direct material cost per unit. Further, it is assumed that the redesigned product requires processing time on Resource M5. In addition, it is assumed that each unit of the product requires more processing time on Resource M3. Resource M5 is assumed to be redesigned such that it is less reliable and less maintainable resulting in a corresponding reduction in per unit acquisition cost. Consequently, the periodic equivalent resource cost per unit of Resource M5 is also reduced. The values for the changed design dependent parameters together with the results obtained from SEDE 1.0 for this design alternative are presented in Table 6.3. All other model input parameters are assumed to be unchanged and correspond to the respective values in the baseline design configuration.

The results presented in Table 6.3 indicate that expected profit from Design Alternative III is \$641,856. This represents a significant improvement over the expected profit resulting from the baseline design (\$634,887). The candidate designs for Product X6 and Resource M5 are retained for further consideration, if necessary. However, for Design Alternative IV, only candidate designs for Product X1 and Resources M2 and M4 are evaluated and Product X6 and Resource M5 are assumed unchanged and their designs correspond to the baseline design.

6.4 Design Alternative IV

In this design alternative, it is assumed that Product X1 is redesigned such that Resource M5 is not utilized for its production. It is further assumed that each unit of the product utilizes more processing time on Resource M1 and less processing time on Resource M6. The direct material cost per unit of Product X1 is also assumed to increase, consequently.

In addition, Resources M2 and M4 are assumed to be less reliable and less maintainable. The periodic equivalent resource cost for both resources is assumed to change correspondingly. The changed design dependent parameter values together with the results obtained from SEDE 1.0 for this alternative are presented in Table 6.4. All other input parameters are assumed to be unchanged and correspond to the respective values in the baseline design configuration.

The results presented in Table 6.4 indicate that expected profit from this design alternative is $645,979, which is a significant improvement over the expected profit resulting from the baseline design ($634,887). The candidate designs for Product X1 and Resources M2 and M4 are retained for Design Alternative V. Additionally, the candidate design for Resource M5 proposed in Design Alternative III is also included in Design Alternative V.

6.5 Design Alternative V

In this design alternative, the candidate designs for Product X1 and Resources M2 and M4 presented in the last design alternative are evaluated together with the candidate design of Resource M5 presented in Design Alternative III. All other model input parameters are assumed to be unchanged and correspond to the respective values in the baseline design configuration. The values for the changed input parameters, together with the results obtained from SEDE 1.0, for this alternative are presented in Table 6.5.

The results presented in Table 6.5 indicate that expected profit from Design Alternative V is $659,979, which is a significant improvement over the expected profit resulting from the baseline design ($634,887). The expected profit resulting from this design alternative is the highest amongst the alternatives evaluated earlier. Therefore, this design alternative can be selected for subsequent implementation.

Table 6.3 Design Alternative III

Design Dependent Parameters, Expected Profit, and Decision Variables	Value
Amount of Resource M3 consumed by a unit of Product X6 (D_{X6M3})	0.25 Hours/Unit
Amount of Resource M5 consumed by a unit of Product X6 (D_{X6M5})	0.60 Hours/Unit
Material cost for Product X6 (MC_{X6})	12.00 $/Unit
Failure rate (λ) for Resource M5	3.5 Failures/Year
Mean corrective maintenance time (M_{ct}) for Resource M5	15.5 Hours
Periodic equivalent resource cost per unit for Resource M5	$ 86,000
Expected profit	$ 641,856
Production quantity for Product X1	1000 Units
Production quantity for Product X2	5000 Units
Production quantity for Product X3	3500 Units
Production quantity for Product X4	2000 Units
Production quantity for Product X5	5000 Units
Production quantity for Product X6	1500 Units
Number of units of Resource M1 to be acquired	2 Units
Number of units of Resource M2 to be acquired	3 Units
Number of units of Resource M3 to be acquired	2 Units
Number of units of Resource M4 to be acquired	3 Units
Number of units of Resource M5 to be acquired	1 Unit
Number of units of Resource M6 to be acquired	1 Unit

Table 6.4 Design Alternative IV

Design Dependent Parameters, Expected Profit, and Decision Variables	Value
Amount of Resource M1 consumed by a unit of Product X1 (D_{X1M1})	1.10 Hours/Unit
Amount of Resource M6 consumed by a unit of Product X1 (D_{X1M6})	0.25 Hours/Unit
Material cost for Product X1 (MC_{X1})	8.00 $/Unit
Failure rate (λ) for Resource M2	10 Failures/Year
Failure rate (λ) for Resource M4	3.5 Failures/Year
Mean corrective maintenance time (M_{ct}) for Resource M2	9 Hours
Mean corrective maintenance time (M_{ct}) for Resource M4	13.5 Hours
Periodic equivalent resource cost per unit for Resource M2	$ 35,000
Periodic equivalent resource cost per unit for Resource M4	$ 90,000
Expected profit	$ 645,979
Production quantity for Product X1	1000 Units
Production quantity for Product X2	5000 Units
Production quantity for Product X3	3500 Units
Production quantity for Product X4	2000 Units
Production quantity for Product X5	4641 Units
Production quantity for Product X6	1500 Units
Number of units of Resource M1 to be acquired	2 Units
Number of units of Resource M2 to be acquired	3 Units
Number of units of Resource M3 to be acquired	2 Units
Number of units of Resource M4 to be acquired	3 Units
Number of units of Resource M5 to be acquired	1 Unit
Number of units of Resource M6 to be acquired	1 Unit

Table 6.5 Design Alternative V

Design Dependent Parameters, Expected Profit, and Decision Variables	Value
Amount of Resource M1 consumed by a unit of Product X1 (D_{X1M1})	1.10 Hours/Unit
Amount of Resource M6 consumed by a unit of Product X1 (D_{X1M6})	0.25 Hours/Unit
Material cost for Product X1 (MC_{X1})	8.00 $/Unit
Failure rate (λ) for Resource M2	10 Failures/Year
Failure rate (λ) for Resource M4	3.5 Failures/Year
Failure rate (λ) for Resource M5	3.5 Failures/Year
Mean corrective maintenance time ($\bar{M}_{ct}$) for Resource M2	9 Hours
Mean corrective maintenance time ($\bar{M}_{ct}$) for Resource M4	13.5 Hours
Mean corrective maintenance time ($\bar{M}_{ct}$) for Resource M5	15.5 Hours
Periodic equivalent resource cost per unit for Resource M2	$ 35,000
Periodic equivalent resource cost per unit for Resource M4	$ 90,000
Periodic equivalent resource cost per unit for Resource M5	$ 86,000
Expected profit	$ 659,979
Production quantity for Product X1	1000 Units
Production quantity for Product X2	5000 Units
Production quantity for Product X3	3500 Units
Production quantity for Product X4	2000 Units
Production quantity for Product X5	4641 Units
Production quantity for Product X6	1500 Units
Number of units of Resource M1 to be acquired	2 Units
Number of units of Resource M2 to be acquired	3 Units
Number of units of Resource M3 to be acquired	2 Units
Number of units of Resource M4 to be acquired	3 Units
Number of units of Resource M5 to be acquired	1 Unit
Number of units of Resource M6 to be acquired	1 Unit

7.0 EXTENDING THE DESIGN EVALUATION MODEL

In this chapter, the simultaneous engineering design evaluation model developed in Chapter 3 is extended. The extended model presented in this chapter is applicable to the constrained-design problem wherein the design alternatives for the products as well as the resources are limited and a complete, a priori, enumeration of all feasible design alternatives is possible. Thus, the extended model permits inclusion of all product and resource design alternatives. This is in contrast to the model developed in Chapter 3 and the baseline and alternative design configurations evaluated in Chapter 5 and in Chapter 6. Those relate to the open ended design environment wherein it is not possible to list, a priori, all feasible design alternatives. Open ended design requires design alternatives to be evaluated as they are generated and not as a predetermined finite set.

7.1 Development of the Constrained-Design Evaluation Model

As stated above, the constrained-design evaluation model relates to the constrained design problem wherein all feasible design alternatives for both, the products as well as the resources, can be exhaustively listed. Product and resource design alternatives are included in the model, thereby eliminating the need to sequentially evaluate all possible alternative design combinations that are generated as a consequence of identification of product and resource design alternatives.

The singular objective of the constrained-design evaluation model is the maximization of expected profit. It is assumed that revenues are generated from two sources: sale of products and sale of manufacturing resources at the end of their useful life. Costs are assumed to be incurred only in the acquisition, utilization, and maintenance of the required manufacturing resources. Manufacturing resource acquisition cost or first cost, maintenance costs over the useful life of the manufacturing resource, and salvage value, if any, at the end of the resource life cycle are treated as a single design dependent parameter, periodic equivalent resource cost. In addition, it is assumed that a fixed product sustaining cost is incurred whenever a product is produced. The objective function can now be stated as in Equation 7.1. Explanation for notations used for the decision variables, parameters and subscripts presented in Equations 7.1 through 7.6 is provided at the end of this section.

$$\sum_{p=1}^{P}\sum_{s=1}^{S} \{S_p - MC_p - RCC_{ps}\} X_{ps} - \sum_{p=1}^{P} C_p Y_p - \sum_{r=1}^{R}\sum_{t=1}^{T} AC_{rt} M_{rt} \tag{7.1}$$

The constrained-design evaluation model requires enumeration of basecase and alternative designs for products as well as manufacturing resources. The identification of alternative designs for the manufacturing resources generates alternative facility configurations. Each alternative facility configuration is one of the set of possible combinations of resource designs such that one and only one design for each resource is included in the facility configuration.[1] Products can be produced on any facility configuration such that resource capacity is not exceeded for all resources and resource designs under consideration. The resource capacity constraint is stated in Equation 7.2.

$$\sum_{p=1}^{P}\sum_{s=1}^{S} RCRT_{rtps} X_{ps} - AK_{rt} M_{rt} \leq 0 \quad \forall r \ \forall t \tag{7.2}$$

Resource consumption per unit product, $RCRT_{rtps}$, must be summed only over those facility configurations in which resource r, of type t, is included. Thus, the value of $RCRT_{rtps}$ is zero for all facility configurations in which resource r, of type t, is not included.

[1] For example, eight facility configurations can exist if the manufacturing facility comprises of three resources each of which have a total of two design alternatives (including the basecase design). See Figure 7.1 "Facility Configurations for the Constrained Design Scenario"

Further, the production quantity for any product, from all possible facility configurations, should not exceed the market demand for that product. The demand constraint is stated in Equation 7.3. The binary variable Y_p takes the value of one, whenever product X_p is produced on any facility configuration.

$$\sum_{s=1}^{S} X_{ps} - MD_p Y_p \leq 0 \quad \forall p \tag{7.3}$$

The constrained-design evaluation model assumes that design alternatives for products as well as manufacturing resources are mutually exclusive. Mutual exclusivity for alternative designs for the required manufacturing resources is imposed by the constraints stated in Equations 7.4 and 7.5.

$$M_{rt} - BM_{rt} YM_{rt} \leq 0 \quad \forall r \ \forall t \tag{7.4}$$

$$\sum_{t=1}^{T} YM_{rt} = 1 \quad \forall t \tag{7.5}$$

It follows that one and only one resource type (or resource alternative) is chosen for each resource. In view of the constraints stated in Equations 7.4 and 7.5, it follows from the resource capacity constraint stated in Equation 7.2, that production is permitted on one and only one facility configuration.[2]

Mutual exclusivity of design alternatives for products is imposed by the constraint stated in Equation 7.6.

---

[2] See constraints labeled CAP11 through CAP32 in Appendix B. Assume that Resource 1 Alternative 1, Resource 2 Alternative 1, and Resource 3 Alternative 1 is selected to be acquired. Thus, available resource capacity for other alternatives for all resources is zero. Consequently, production is not allowed on any of the facility configurations in which the other resource alternatives are included. It follows that production is allowed on one and only one facility configuration (Facility Configuration 1, in this case) for all products.

$$Y_{p_b} + \sum_{a} Y_{p_a} \le 1 \quad \forall p \tag{7.6}$$

For the sake of modeling simplicity, design alternatives for products are not represented by a separate subscript. Instead, the set of "P" products is assumed to include both basecase designs as well as design alternatives for all products under consideration. The model treats a design alternative for a product as another product. The constraint stated in Equation 7.6 ensures that one and only one design alternative for a product is chosen for production.

The constrained-design evaluation model is summarized and stated in Model III.

Model III

Maximize:

$$\sum_{p=1}^{P}\sum_{s=1}^{S} \{S_p - MC_p - RCC_{ps}\} X_{ps} - \sum_{p=1}^{P} C_p Y_p - \sum_{r=1}^{R}\sum_{t=1}^{T} AC_{rt} M_{rt}$$

Subject to:

$$\sum_{p=1}^{P}\sum_{s=1}^{S} RCRT_{rtps} X_{ps} - AK_{rt} M_{rt} \le 0 \quad \forall r \ \forall t$$

$$\sum_{s=1}^{S} X_{ps} - MD_p Y_p \le 0 \quad \forall p$$

$$M_{rt} - BM_{rt} YM_{rt} \le 0 \quad \forall r \ \forall t$$

$$\sum_{t=1}^{T} YM_{rt} = 1 \quad \forall t$$

$$Y_{p_b} + \sum_{a} Y_{p_a} \le 1 \quad \forall p$$

Where:

Decision variables:

X_{ps} : Production quantity of product p by facility alternative s

M_{rt} : Number of units of resource r of type t to acquire

Y_p : Product sustaining indicator; 0 - 1 variable, 1 if product p is produced

YM_{rt} : Resource sustaining indicator; 0 - 1 variable, 1 if resource r of type t is acquired

Parameters:

AC_{rt} : Periodic equivalent resource cost per unit of M

AK_{rt} : Available capacity per unit of resource r of type t

BM_p : A number bigger than production quantity of product p

BM_{rt} : A number bigger than number of resources r of type t to be acquired

C_p :Product sustaining cost of product p

MC_p : Direct material cost per unit of product p

MD_p : Market demand for product p

RCC_{ps} : Total resource consumption cost per unit of product p produced by facility s

$RCRT_{rtps}$: Amount of resource r, type t, consumed by product p produced by facility s

S_p : Sales price per unit of product p

Subscripts:

p : Product, includes basecase and alternative designs, with a maximum of P

p_a : Alternative design for product p

p_b : Basecase design for product p

r : Resource, with a maximum of R

s : Facility configuration, with a maximum of S such that $S = T^R$

t : Resource basecase and alternative design, with a maximum of T

Design evaluation using Model III does not utilize the design dependent parameter approach for indirect system experimentation and combines the design space with the optimization space. Model III includes the set of design dependent parameters into the set of decision variables. The design evaluation function is thus changed from the form:

$$E \quad = \quad f(X, Y_d, Y_i) \tag{7.7}$$

to the form:

$$E \quad = \quad f(X_i, Y_j) \tag{7.8}$$

The economic evaluation function is similar to that proposed by Churchman, Ackoff, and Arnoff [3]. They have proposed that system effectiveness is a function of the set of variables under control (X_i) and the set of variables not subject to control (Y_j) and that there exist values for the controllable variables which could optimize the system in the face of uncontrollable variables.

7.2 Assumptions of the Extended Model

In addition to the assumptions stated for Model II, Model III is further limited by the following assumptions:

1. It is assumed that all possible product and resource design alternatives can be exhaustively listed prior to model implementation.
2. The model assumes that the product and resource design alternatives are mutually exclusive.
3. It is assumed that the list of 'P' products is exhaustive in that it contains basecase as well as alternative designs for all products.

4. It is assumed that a maximum of 'T' alternative designs can be identified for each of the 'R' resources. These 'T' alternative resource designs are exhaustive and contain basecase designs as well as alternative designs for resources.

7.3 Evaluation of a Constrained-Design Scenario

In this section, the applicability of Model III is demonstrated for a hypothetical constrained design application scenario. It is assumed that three products are being considered for production and all of these three products require a maximum of three manufacturing resources. It is also assumed that one alternative design, in addition to the basecase design, exists for two of the three products. In addition, each of the three resources have a total of two design alternatives. Consequently, there exist eight alternative facility configurations which are enumerated in Figure 7.1. The values for the input parameters of the model are defined in Tables 7.1 through 7.4.

FACILITY CONFIGURATION - 1
(Resource 1, Alternative 1), (Resource 2, Alternative 1) and (Resource 3, Alternative 1)
FACILITY CONFIGURATION - 2
(Resource 1, Alternative 1), (Resource 2, Alternative 1) and (Resource 3, Alternative 2)
FACILITY CONFIGURATION - 3
(Resource 1, Alternative 1), (Resource 2, Alternative 2) and (Resource 3, Alternative 1)
FACILITY CONFIGURATION - 4
(Resource 1, Alternative 1), (Resource 2, Alternative 2) and (Resource 3, Alternative 2)
FACILITY CONFIGURATION - 5
(Resource 1, Alternative 2), (Resource 2, Alternative 1) and (Resource 3, Alternative 1)
FACILITY CONFIGURATION - 6
(Resource 1, Alternative 2), (Resource 2, Alternative 1) and (Resource 3, Alternative 2)
FACILITY CONFIGURATION - 7
(Resource 1, Alternative 2), (Resource 2, Alternative 2) and (Resource 3, Alternative 1)
FACILITY CONFIGURATION - 8
(Resource 1, Alternative 2), (Resource 2, Alternative 2) and (Resource 3, Alternative 2)

Figure 7.1 Facility Configurations for the Constrained Design Scenario

Table 7.1 Product Related Data for the Constrained Design Scenario

Products	Sales Price (S_p) Dollars/Unit	Market Demand (MD_p) Units	Product Sustaining Cost (C_p) Dollars	Material Cost (MC_p) Dollars/Unit
Baseline Design for Product 1 (X1)	150.00	5000	10,000	6.00
Alternative Design for Product 1 (X2)	150.00	5000	10,000	7.00
Baseline Design for Product 2 (X3)	135.00	3500	10,000	6.50
Alternative Design for Product 2 (X4)	135.00	3500	10,000	7.50
Baseline Design for Product 3 (X5)	95.00	2500	10,000	10.00

Table 7.2 Resource Consumption Data for the Constrained Design Scenario

Products	X1	X2	X3	X4	X5
Resource 1, Alternative 1	0.50	1.00	0.40	1.50	1.50
Resource 1, Alternative 2	0.60	1.30	0.30	1.80	1.50
Resource 2, Alternative 1	0.70	0.70	2.00	0.60	0.90
Resource 2, Alternative 2	0.90	0.90	2.70	0.75	1.10
Resource 3, Alternative 1	0.30	0.40	0.50	0.20	0.70
Resource 3, Alternative 2	0.35	0.70	0.60	0.30	0.95

Table 7.3 Resource Related Data for the Constrained Design Scenario

Resources	Periodic Equivalent Resource Cost (AC_{rt}) Dollars	Unit Consumption Cost (C_{pr}) Dollars/Hour	Installed Capacity (IK_r) Hours/Year
Resource 1, Alternative 1	30,000	7.50	8760
Resource 1, Alternative 2	40,000	7.00	8760
Resource 2, Alternative 1	75,000	10.00	8760
Resource 2, Alternative 2	95,000	11.75	8760
Resource 3, Alternative 1	100,000	9.00	8760
Resource 3, Alternative 2	85,000	10.25	8760

Table 7.4 Reliability and Maintainability Data for the Constrained Design Scenario

Resources	Failure Rate (λ) Times/Year	Preventive Maintenance Rate (fpt) Times/Year	Mean Preventive Maintenance Time (M_{pt}) Hours	Mean Corrective Maintenance Time (M_{ct}) Hours
Resource 1, Alternative 1	5	4	1	5
Resource 1, Alternative 2	8	4	1	8
Resource 2, Alternative 1	2	4	3	9
Resource 2, Alternative 2	3	4	4	12
Resource 3, Alternative 1	3	4	5	13
Resource 3, Alternative 2	4	4	6	18

Data tables corresponding to Tables 7.1 through 7.4 were defined in Paradox to store input data for Model III. The Model was solved using XPRESS-MP. Table 7.5 contains the optimal values for expected profits as well as for the decision variables of the model. The simultaneous engineering design evaluation software application - SEDE 1.0, developed in Chapter 4, was not used to implement Model III since it was developed specifically for Model II.

Table 7.5 Expected Profit and Optimal Values for Decision Variables for the Constrained Design Scenario

Expected Profit and Decision Variables	Optimal Value
Expected Profit	$ 913,450
Production quantity for Product X1 produced on facility configuration 1	5000 Units
Production quantity for Product X2 produced on facility configuration 1	0 Units
Production quantity for Product X3 produced on facility configuration 1	0 Units
Production quantity for Product X4 produced on facility configuration 1	3500 Units
Production quantity for Product X5 produced on facility configuration 1	2500 Units
Number of units of Resource 1, Alternative 1 to be acquired	2 Units
Number of units of Resource 1, Alternative 2 to be acquired	0 Units
Number of units of Resource 2, Alternative 1 to be acquired	1 Unit
Number of units of Resource 2, Alternative 2 to be acquired	0 Units
Number of units of Resource 3, Alternative 1 to be acquired	1 Unit
Number of units of Resource 3, Alternative 2 to be acquired	0 Units

8.0 SUMMARY AND CONCLUSIONS

This final chapter summarizes the contents of this thesis and presents conclusions about the simultaneous engineering design evaluation methodology. It then provides recommendations for extended research in this subject area.

8.1 Thesis Summary

This thesis presents a design evaluation methodology for candidate product and manufacturing resource designs that result from simultaneous engineering design activity. This design evaluation methodology makes use of the design dependent parameter approach to evaluate these alternative design configurations.

The first objective of this research was to develop a design evaluation model that could be applied during the simultaneous engineering process to evaluate product and manufacturing resource design alternatives against a unique and singular objective. Expected profit resulting from the implementation of the design configuration was selected as the economic evaluation measure. The design evaluation model was developed from Moolman's aggregate capital budgeting model [13, p.177]. It was modified to explicitly model failure rate, preventive maintenance rate, mean preventive maintenance time , and mean corrective maintenance time for the manufacturing resources. To ease modeling, these parameters were reduced to a single design dependent parameter - achieved availability.

The second objective of this research effort was to develop an integrated, menu based, software tool to facilitate the simultaneous engineering design evaluation process. This software application, called SEDE 1.0, implements the design evaluation model using XPRESS-MP, a mathematical programming modeling language and mixed integer optimizer. SEDE 1.0 permits input data for the design evaluation model to be stored in tables created using Paradox, a relational database management system. Data is read directly from the Paradox tables at the time of matrix generation at the time of model generation. This interactive linkage between XPRESS-MP and Paradox provides for efficient data handling and effective model implementation. Thus, multiple runs of the design evaluation model to evaluate candidate design scenarios are quick and easy.

The third objective of the research was to demonstrate the applicability and use of the design evaluation model during simultaneous engineering design activity. To demonstrate the model, a hypothetical baseline simultaneous engineering design configuration as well as five alternative design configurations were evaluated using SEDE 1.0. The relationship between resource mean time between failure, resource mean corrective maintenance time, and expected profit was also determined for the baseline design configuration.

Finally, the design evaluation model was modified so as to be applicable to the constrained design problem where it is possible to exhaustively list all feasible design alternatives for the products as well as the manufacturing resources. The extended constrained-design evaluation model considers product and resource design alternatives to be mutually exclusive. The model was demonstrated for a hypothetical constrained-design scenario. The design evaluation methodology for the constrained-design problem did not make use of the design dependent parameter approach.

8.2 Conclusions

The design dependent parameter approach can be applied to the simultaneous engineering design evaluation process. It enables the simultaneous engineering design team to evaluate each candidate design alternative using the design evaluation model developed in this thesis. The design evaluation methodology permits designers to stumble through the feasible design space and thus determine, for subsequent implementation, the product and resource design alternative that results in the highest expected profit.

In addition, it is easier to implement and use mathematical programming planning models for corporate planning if the modeling language or matrix generator is interactively linked to a relational database management system. Data handling, manipulation, and storage is made significantly easier with this integration. The interdependence and non-stationarity of model input parameters makes model implementation difficult for standalone life sized models.

SEDE 1.0, the simultaneous engineering design evaluation software application, shows promise as both, a business policy making and an educational tool. It serves as an excellent tool to link product and resource or facility design configurations to profits that can be generated by these design configurations. As was discussed in Section 1.3, existing simultaneous or concurrent engineering tools have addressed the issues of improving the product design process as well as the resource design process in isolation. SEDE 1.0 bridges this gap and provides for effective comparison of alternative design configurations using expected profit as the economic evaluation measure. To be of use as a business policy making tool, SEDE 1.0 can be easily extended to evaluate larger life like problems involving a greater number of resources and products.

8.3 Extended Research Opportunities

The design evaluation models developed in this study do not make a distinction between activities and resources. Hence, it is assumed that costs are incurred in the acquisition of resources as well as in the utilization of resources. However, Moolman's model [13, p. 177] derives from the principles of activity based costing and assumes that costs are incurred in the acquisition of resources and by the utilization of resources in the form of activities. A research opportunity exists in including utilization costs for activities into the model. Also, another level of variability for activities can be introduced into the model - resource sustaining costs. It can be argued that a resource sustaining cost is incurred each time a particular resource type is acquired. This cost would include training facility costs, personnel training costs, cost of spare parts inventory required for maintenance purposes etc.. The resource sustaining cost would not be directly variable with the number of units of a resource type, but would be incurred each time a new resource type is acquired. For the constrained-design scenario where the mutual exclusivity of product and resource alternatives is relaxed, the resource sustaining cost would minimize the number of resource alternatives that are selected in the optimal design configuration.

In real-life situations, parameters such as market demand and the sales price for products are inherently stochastic in nature. These stochastic parameters are usually best-fit to a deterministic value to conform to the linear programming requirement of a deterministic environment. A research opportunity exists in modeling these stochastic parameters by using stochastic linear programming and chance-constrained programming techniques.

The design evaluation models could also be extended to consider multiple planning periods. Design evaluation models herein do not presently consider the sequence of production processes required to manufacture the products under consideration. A research opportunity exists for extending the design evaluation models so as to include the sequence or routing of the manufacturing resources. This would involve introducing additional parameters into the model to model delay times and time spent in queues. Stochastic programming techniques could also be used here if delay times and the time spent in queues are modeled as stochastic parameters.

REFERENCES

[1] Bedworth, D. D. and Bailey, J. E. (1987) "Integrated Production Control Systems", John Wiley.

[2] Blanchard, B. S. and Fabrycky, W. J. (1990) "Systems Engineering and Analysis", Prentice Hall.

[3] Churchman, C. W., Ackoff, R. L. and Arnoff, E. L. (1957) "Introduction to Operations Research", John Wiley.

[4] Fabrycky, W. J. (1992) "Indirect Experimentation for System Optimization: A Paradigm based on Design Dependent Parameters", Proceedings, Second Annual International Symposium, National Council on Systems Engineering, Seattle, Washington, July 1992.

[5] Fabrycky, W. J. and Blanchard, B. S. (1991) "Life Cycle Cost and Economic Analysis", Prentice Hall.

[6] Fourer, R. (1983) "Modeling Language versus Matrix Generators for Linear Programming", ACM Transactions on Mathematical Software, Vol. 9, No. 2, June 1983, pp. 143-183.

[7] Gatenby, D.A., Lee, P.M., Howard, R.E., Hushyar, K., Layendecker, R., and Wesner, J. (1994) "Concurrent Engineering: An Enabler for Fast, High Quality Product Realization", AT&T Technical Journal, Vol. 73, No. 1, January-February 1994, pp. 34-47.

[8] Hirshfeld, D. S. (1984) "An Overview of Mathematical Programming for Strategic Planning", Optimization models for strategic planning, Elsevier Science Publishers.

[9] Hirshfeld, D. S. (1990) "Some Thoughts on Mathematical Programming Practice in the Nineties", Interfaces, Vol. 20(3), pp. 65-79.

[10] Jo, H. H., Parsaei H. R. and Sullivan, W. S. (1993) "Concurrent Engineering: Contemporary issues and Modern Design Tools", Edited by Parsaei, H. R. and Sullivan, W. S., Chapman and Hall, pp. 3-23.

[11] Kalpakjian, S. (1992) “Manufacturing Engineering and Technology”, Addison Wesley.

[12] Matin, A. and Evans, S. (1992) “Project Planning in a Concurrent Engineering Environment”, IEE Conference Publication, n. 359, IEE, England, pp. 298-303.

[13] Moolman, G. C. (1994) “An Aggregate Capital Budgeting Model using a Product Portfolio approach”, Ph. D. Dissertation, Virginia Polytechnic Institute and State University.

[14] Noble, J. S. (1993) “Concurrent Engineering: Contemporary Issues and Modern Design Tools”, Edited by Parsaei, H. R. and Sullivan, W. S., Chapman and Hall, pp. 352-371.

[15] Noble, J. S. and Tanchoco, J. M. A. (1993) “Concurrent Engineering: Contemporary Issues and Modern Design Tools”, Edited by Parsaei, H. R. and Sullivan, W. S., Chapman and Hall, pp. 401-436.

[16] Shapiro, J. F. (1984) “Practical Experiences with Optimization Models”, Optimization models for strategic planning, Elsevier Science Publishers.

[17] Shim, J. K. and Siegel (1993) “Encyclopedic Dictionary of Accounting and Finance”, Prentice Hall.

[18] Weingartner, H. M. (1967) “Mathematical Programming and the Analysis of Capital Budgeting Problems”, Markham Publishing Company.

[19] Whitaker, D. and Brown, S. (1991) “Linear Program Modeling with Databases”, Computers in Operations Research, Vol. 18, No. 1, pp. 33-41.

[20] Williams, H. P. (1993) “Model Building in Mathematical Programming”, John Wiley.

[21] Williamson, I. P. (1992) “Business Transformation through Simultaneous Engineering of Product and Process”, IEE Conference Publication, n. 359, IEE, England, pp. 59-64.

[22] Yoshimura, M. (1993) "Concurrent Engineering: Contemporary issues and Modern Design Tools", Edited by Parsaei H. R. and Sullivan, W. S., Chapman and Hall, pp. 159-183.

[23] Ziemke, M. C. and Spann, M. S. (1993) "Concurrent Engineering: Contemporary issues and Modern Design Tools", Edited by Parsaei, H. R. and Sullivan, W. S., Chapman and Hall, pp. 24-41.

APPENDICES

APPENDIX A

XPRESS-MP INPUT FILE FOR DESIGN EVALUATION MODEL

```
!              SIMULTANEOUS ENGINEERING DESIGN EVALUATION MODEL
!
!                              CONSIDERS SIX PRODUCTS & SIX RESOURCES
!
LET PROD = 6                   ! SIX PRODUCTS
LET RES = 6                    ! SIX RESOURCES
!
VARIABLES                      ! INTRODUCE THE VARIABLES
!
X(P=1:PROD)                    ! PRODUCTION QUANTITIES FOR PRODUCTS
Y(P=1:PROD)                    ! PRODUCT SUSTAINING BINARY VARIABLES
M(R=1:RES)                     ! NUMBER OF UNITS OF RESOURCES TO BE ACQUIRED
!
TABLES                         ! CREATE THE DATA TABLES
!
DUMMY1(PROD)                   ! READS SALES PRICE FROM PARADOX
SP(PROD)                       ! SALES PRICE FOR PRODUCTS
DUMMY2(PROD)                   ! READS MARKET DEMAND FROM PARADOX
MD(PROD)                       ! MARKET DEMAND OF PRODUCTS
BMP(PROD)                      ! NO. GREATER THAN PROBABLE PRODUCTION QUANTITY
DUMMY3(PROD)                   ! READS PRODUCT SUSTAINING COST FROM PARADOX
CP(PROD)                       ! PRODUCT SUSTAINING COST
DUMMY4(PROD)                   ! READS MATERIAL COST FROM PARADOX
MC(PROD)                       ! MATERIAL COST PER UNIT PRODUCT
DUMMY5(RES,PROD)               ! READS RESOURCE CONSUMPTION FROM PARADOX
DPR(RES,PROD)                  ! RESOURCE CONSUMPTION
DUMMY6(RES)                    ! READS ACQUISITION COST FROM PARADOX
CR(RES)                        ! ACQUISITION COST PER UNIT RESOURCE
DUMMY7(RES)                    ! READS COST PER UNIT RESOURCE FROM PARADOX
CPR(RES)                       ! COST PER UNIT OF RESOURCE CONSUMED
DUMMY8(RES)                    ! READS FAILURE RATE FROM PARADOX
FR(RES)                        ! FAILURE RATE
DUMMY9(RES)                    ! READS PREVEN. MAINT. RATE FROM PARADOX
PMR(RES)                       ! PREVENTIVE MAINTENANCE RATE
DUMMY10(RES)                   ! READS PREVEN. MAINT. TIME FROM PARADOX
MPT(RES)                       ! MEAN PREVENTIVE MAINTENENCE TIME
DUMMY11(RES)                   ! READS CORRECT. MAINT. TIME FROM PARADOX
MCT(RES)                       ! MEAN CORRECTIVE MAINTENENCE TIME
DUMMY12(RES)                   ! READS INSTALLED CAPACITY FROM PARADOX
IC(RES)                        ! INSTALLED CAPACITY OF RESOURCE
KRT(RES)                       ! AVAILABLE CAPACITY OF RESOURCE
CONTRI(PROD)                   ! CONTRIBUTION OF EACH PRODUCT
!
CONNECT paradox                ! READ DATA TABLES FROM PARADOX
!
```

```
DISKDATA -c
!
DUMMY1=C:\SEDE\PDOX35\TABLE1 (SALES_PRICE)
!
DUMMY2=C:\SEDE\PDOX35\TABLE1 (MARKET_DEMAND)
!
DUMMY3=C:\SEDE\PDOX35\TABLE1 (PRODUCT_SUSTAINING_COST)
!
DUMMY4=C:\SEDE\PDOX35\TABLE1 (MATERIAL_COST)
!
DUMMY5=C:\SEDE\PDOX35\TABLE2 (X1,X2,X3,X4,X5,X6)
!
DUMMY6=C:\SEDE\PDOX35\TABLE3 (ACQUISITION_COST)
!
DUMMY7=C:\SEDE\PDOX35\TABLE3 (UNIT_CONSUMPTION_COST)
!
DUMMY8=C:\SEDE\PDOX35\TABLE4 (FAILURE_RATE)
!
DUMMY9=C:\SEDE\PDOX35\TABLE4 (PREVENTIVE_MAINT._RATE)
!
DUMMY10=C:\SEDE\PDOX35\TABLE4 (MEAN_P.MAINT._TIME)
!
DUMMY11=C:\SEDE\PDOX35\TABLE4 (MEAN_C.MAINT._TIME)
!
DUMMY12=C:\SEDE\PDOX35\TABLE3 (INSTALLED_CAPACITY)
!
DISCONNECT
!
ASSIGN                              ! COMPUTE TABLE VALUES
!
SP(P=1:PROD) = DUMMY1(P)
MD(P=1:PROD) = DUMMY2(P)
CP(P=1:PROD) = DUMMY3(P)
MC(P=1:PROD) = DUMMY4(P)
DPR(R=1:RES,P=1:PROD) = DUMMY5(R,P)
CR(R=1:RES) = DUMMY6(R)
CPR(R=1:RES) = DUMMY7(R)
FR(R=1:RES) = DUMMY8(R)
PMR(R=1:RES) = DUMMY9(R)
MPT(R=1:RES) = DUMMY10(R)
MCT(R=1:RES) = DUMMY11(R)
IC(R=1:RES) = DUMMY12(R)
BMP(P=1:PROD) = MD(P) + 1
KRT(P=1:PROD) = IC(P)/(1 + FR(P)*MCT(P)/8760 + PMR(P)*MPT(P)/8760)
CONTRI(P=1:PROD) = SP(P) - SUM(R=1:RES) DPR(R,P)*CPR(P) - MC(P)
!
PRINT
!
DUMMY1
SP
DUMMY2
```

```
MD
BMP
DUMMY3
CP
DUMMY4
MC
DUMMY5
DPR
DUMMY6
CR
DUMMY7
CPR
DUMMY8
FR
DUMMY9
PMR
DUMMY10
MPT
DUMMY11
MCT
DUMMY12
IC
KRT
CONTRI
!
CONSTRAINTS                 ! INTRODUCE OBJECTIVE FUNCTION & CONSTRAINTS
!
PROFIT:                     SUM(P=1:PROD) CONTRI(P) * X(P) &
                            - SUM(P=1:PROD) CP(P) * Y(P) &
                            - SUM(R=1:RES) CR(R)*M(R) $
!
CAP(R=1:RES):               SUM(P=1:PROD) DPR(R,P) * X(P) - KRT(R) * M(R) < 0
!
DEM(P=1:PROD):              X(P) < MD(P)
!
PSCINC(P=1:PROD):           X(P) - BMP(P) * Y(P)  < 0
!
BOUNDS                      ! DEFINING BINARY & INTEGER VARIABLES
!
X(P=1:PROD) .PI.30          ! PARTIAL INTEGER, TAKES CONTINUOUS VALUES OVER 30
Y(P=1:PROD) .BV.            ! PRODUCT SUSTAINING VARIABLE TAKES 0 - 1 VALUES
M(R=1:RES) .UI.30           ! NUMBER OF RESOURCES TAKE INTEGER VALUES
!
GENERATE
```

APPENDIX B

XPRESS-MP INPUT FILE FOR CONSTRAINED-DESIGN EVALUATION MODEL

```
!                               CONSTRAINED-DESIGN EVALUATION MODEL
!
!                               CONSIDERS 3 RESOURCES OF 2 TYPES & 5 PRODUCTS
!
!                               ONLY ONE DESIGN ALTERNATIVE CAN BE SELECTED FOR
                                EACH PRODUCT AND RESOURCE
!
!                               PRODUCTS X1 & X2 AND X3 & X4 ARE ALTERNATIVES FOR
                                SAME PRODUCT AND ONLY ONE OF THE TWO IS ALLOWED
                                TO BE PRODUCED
!
LET MAXRES=30                   ! MAXIMUM PERMITTED VALUE FOR M(R=1:3,T=1:2)
!
VARIABLES                       ! INTRODUCE THE VARIABLES
!
X(P=1:5,S=1:8)                  ! PRODN. QUANTITIES FOR PRODUCT "P" BY SEQUENCE "S"
M(R=1:3,T=1:2)                  ! NUMBER OF UNITS OF RESOURCES TO BE ACQUIRED
Y(P=1:5)                        ! TOTAL PRODUCT SUS. BINARY VARIABLES
                                FOR PRODUCT "P"
YM(R=1:3,T=1:2)                 ! RESOURCE SUSTAINING BINARY VARIABLES
!
TABLES                          ! CREATE THE DATA TABLES
!
SP(5)                           ! SALES PRICE FOR PRODUCTS
MD(5)                           ! MARKET DEMAND OF PRODUCTS
CP(5)                           ! PRODUCT SUSTAINING COST
MC(5)                           ! MATERIAL COST PER UNIT PRODUCT
DPRT(3,2,5)                     ! RESOURCE CONSUMPTION
ACQRT(3,2)                      ! ACQUISITION COST PER UNIT RESOURCE
CRT(3,2)                        ! COST PER UNIT OF RESOURCE CONSUMED
FR(3,2)                         ! FAILURE RATE
PMR(3,2)                        ! PREVENTIVE MAINTENANCE RATE
MPT(3,2)                        ! MEAN PREVENTIVE MAINTENENCE TIME
MCT(3,2)                        ! MEAN CORRECTIVE MAINTENENCE TIME
IC(3,2)                         ! INSTALLED CAPACITY OF RESOURCE
KRT(3,2)                        ! AVAILABLE CAPACITY OF RESOURCE
BMP(5)                          ! NO. GREATER THAN PROBABLE PRODUCTION QUANTITY
RCC(5,8)                        ! RESOURCE CONSUMPTION COST
RCCRT(3,2,5)                    ! RES. CONSUMP. COST FOR RES. R, TYPE T FOR PRODUCT P
CONTRI(5,8)                     ! CONTRIBUTION OF PRODUCT P, SEQUENCE S
DUMMY1(6,5)                     ! READS RESOURCE CONSUMPTION FROM PARADOX
DUMMY2(6)                       ! READS ACQUISITION COST FROM PARADOX
```

```
DUMMY3(6)               ! READS UNIT RESOURCE CONSUMPTION COST FROM
                        PARADOX
DUMMY4(6)               ! READS FAILURE RATE FROM PARADOX
DUMMY5(6)               ! READS PREVEN. MAINT. RATE  FROM PARADOX
DUMMY6(6)               ! READS PREVEN. MAINT. TIME FROM PARADOX
DUMMY7(6)               ! READS CORRECTIVE MAINT. TIME FROM PARADOX
DUMMY8(6)               ! READS INSTALLED CAPACITY FROM PARADOX
DUMMY9(5)               ! READS SALES PRICE FROM PARADOX
DUMMY10(5)              ! READS MARKET DEMAND FROM PARADOX
DUMMY11(5)              ! READS PRODUCT SUSTAINING COST FROM PARADOX
DUMMY12(5)              ! READS MATERIAL COST FROM PARADOX
!
CONNECT paradox         ! READ DATA TABLES FROM PARADOX
!
DISKDATA -c
DUMMY1=C:\BASANT\PDOX35\RESCON5 (X1,X2,X3,X4,X5)
DUMMY2=C:\BASANT\PDOX35\ACTIREL5 (ACQUISITION_COST)
DUMMY3=C:\BASANT\PDOX35\ACTIREL5 (UNIT_CONSUMPTION_COST)
DUMMY4=C:\BASANT\PDOX35\ACTIREL5 (FAILURE_RATE)
DUMMY5=C:\BASANT\PDOX35\ACTIREL5 (PREVENTIVE_MAINT._RATE)
DUMMY6=C:\BASANT\PDOX35\ACTIREL5 (MEAN_P.MAINT._TIME)
DUMMY7=C:\BASANT\PDOX35\ACTIREL5 (MEAN_C.MAINT._TIME)
DUMMY8=C:\BASANT\PDOX35\ACTIREL5 (INSTALLED_CAPACITY)
SP=C:\BASANT\PDOX35\PRODDAT5 (SALES_PRICE)
MD=C:\BASANT\PDOX35\PRODDAT5 (MARKET_DEMAND)
CP=C:\BASANT\PDOX35\PRODDAT5 (PRODUCT_SUSTAINING_COST)
MC=C:\BASANT\PDOX35\PRODDAT5 (MATERIAL_COST_PER_UNIT)
!
DISCONNECT
!
DATA
!
DPRT(1,1,1)=DUMMY1(1,1),DUMMY1(1,2),DUMMY1(1,3),DUMMY1(1,4),DUMMY1(1,5)
DPRT(1,2,1)=DUMMY1(2,1),DUMMY1(2,2),DUMMY1(2,3),DUMMY1(2,4),DUMMY1(2,5)
DPRT(2,1,1)=DUMMY1(3,1),DUMMY1(3,2),DUMMY1(3,3),DUMMY1(3,4),DUMMY1(3,5)
DPRT(2,2,1)=DUMMY1(4,1),DUMMY1(4,2),DUMMY1(4,3),DUMMY1(4,4),DUMMY1(4,5)
DPRT(3,1,1)=DUMMY1(5,1),DUMMY1(5,2),DUMMY1(5,3),DUMMY1(5,4),DUMMY1(5,5)
DPRT(3,2,1)=DUMMY1(6,1),DUMMY1(6,2),DUMMY1(6,3),DUMMY1(6,4),DUMMY1(6,5)
!
ACQRT(1,1)=DUMMY2(1),DUMMY2(2)
ACQRT(2,1)=DUMMY2(3),DUMMY2(4)
ACQRT(3,1)=DUMMY2(5),DUMMY2(6)
!
CRT(1,1)=DUMMY3(1),DUMMY3(2)
CRT(2,1)=DUMMY3(3),DUMMY3(4)
CRT(3,1)=DUMMY3(5),DUMMY3(6)
!
FR(1,1)=DUMMY4(1),DUMMY4(2)
FR(2,1)=DUMMY4(3),DUMMY4(4)
FR(3,1)=DUMMY4(5),DUMMY4(6)
!
```

```
PMR(1,1)=DUMMY5(1),DUMMY5(2)
PMR(2,1)=DUMMY5(3),DUMMY5(4)
PMR(3,1)=DUMMY5(5),DUMMY5(6)
!
MPT(1,1)=DUMMY6(1),DUMMY6(2)
MPT(2,1)=DUMMY6(3),DUMMY6(4)
MPT(3,1)=DUMMY6(5),DUMMY6(6)
!
MCT(1,1)=DUMMY7(1),DUMMY7(2)
MCT(2,1)=DUMMY7(3),DUMMY7(4)
MCT(3,1)=DUMMY7(5),DUMMY7(6)
!
IC(1,1)=DUMMY8(1),DUMMY8(2)
IC(2,1)=DUMMY8(3),DUMMY8(4)
IC(3,1)=DUMMY8(5),DUMMY8(6)
!
ASSIGN                          ! COMPUTE REMAINING TABLE VALUES
!
KRT(R=1:3,T=1:2) = IC(R,T) / (1+FR(R,T)*MCT(R,T)/8760+PMR(R,T)*MPT(R,T)/8760)
!
BMP(P=1:5) = MD(P) + 1
!
RCCRT(R=1:3,T=1:2,P=1:5) = DPRT(R,T,P) * CRT(R,T)
!
RCC(P=1:5,S=1:1) = RCCRT(1,1,P) + RCCRT(2,1,P) + RCCRT(3,1,P)
RCC(P=1:5,S=2:2) = RCCRT(1,1,P) + RCCRT(2,1,P) + RCCRT(3,2,P)
RCC(P=1:5,S=3:3) = RCCRT(1,1,P) + RCCRT(2,2,P) + RCCRT(3,1,P)
RCC(P=1:5,S=4:4) = RCCRT(1,1,P) + RCCRT(2,2,P) + RCCRT(3,2,P)
RCC(P=1:5,S=5:5) = RCCRT(1,2,P) + RCCRT(2,1,P) + RCCRT(3,1,P)
RCC(P=1:5,S=6:6) = RCCRT(1,2,P) + RCCRT(2,1,P) + RCCRT(3,2,P)
RCC(P=1:5,S=7:7) = RCCRT(1,2,P) + RCCRT(2,2,P) + RCCRT(3,1,P)
RCC(P=1:5,S=8:8) = RCCRT(1,2,P) + RCCRT(2,2,P) + RCCRT(3,2,P)
!
CONTRI(P=1:5,S=1:8) = SP(P) - MC(P) - RCC(P,S)
!
PRINT SP
PRINT MD
PRINT CP
PRINT MC
PRINT DPRT
PRINT ACQRT
PRINT CRT
PRINT FR
PRINT PMR
PRINT MPT
PRINT MCT
PRINT IC
PRINT KRT
PRINT BMP
PRINT RCC
PRINT RCCRT
```

```
PRINT CONTRI
!

!
CONSTRAINTS                  ! INTRODUCE OBJECTIVE FUNCTION & CONSTRAINTS
!
PROFIT:                      SUM(P=1:5,S=1:8) CONTRI(P,S) * X(P,S) &
                             - SUM(P=1:5) CP(P) * Y(P) &
                             - SUM(R=1:3,T=1:2) ACQRT(R,T) * M(R,T) $
!
CAP11:                       SUM(P=1:5) DPRT(1,1,P) * X(P,1) &
                             + SUM(P=1:5) DPRT(1,1,P) * X(P,2) &
                             + SUM(P=1:5) DPRT(1,1,P) * X(P,3) &
                             + SUM(P=1:5) DPRT(1,1,P) * X(P,4) - KRT(1,1)*M(1,1) < 0
!
CAP12:                       SUM(P=1:5) DPRT(1,2,P) * X(P,5) &
                             + SUM(P=1:5) DPRT(1,2,P) * X(P,6) &
                             + SUM(P=1:5) DPRT(1,2,P) * X(P,7) &
                             + SUM(P=1:5) DPRT(1,2,P) * X(P,8) - KRT(1,2)*M(1,2) < 0
!
CAP21:                       SUM(P=1:5) DPRT(2,1,P) * X(P,1) &
                             + SUM(P=1:5) DPRT(2,1,P) * X(P,2) &
                             + SUM(P=1:5) DPRT(2,1,P) * X(P,5) &
                             + SUM(P=1:5) DPRT(2,1,P) * X(P,6) - KRT(2,1)*M(2,1) < 0
!
CAP22:                       SUM(P=1:5) DPRT(2,2,P) * X(P,3) &
                             + SUM(P=1:5) DPRT(2,2,P) * X(P,4) &
                             + SUM(P=1:5) DPRT(2,2,P) * X(P,7) &
                             + SUM(P=1:5) DPRT(2,2,P) * X(P,8) - KRT(2,2)*M(2,2) < 0
!
CAP31:                       SUM(P=1:5) DPRT(3,1,P) * X(P,1) &
                             + SUM(P=1:5) DPRT(3,1,P) * X(P,3) &
                             + SUM(P=1:5) DPRT(3,1,P) * X(P,5) &
                             + SUM(P=1:5) DPRT(3,1,P) * X(P,7) - KRT(3,1)*M(3,1) < 0
!
CAP32:                       SUM(P=1:5) DPRT(3,2,P) * X(P,2) &
                             + SUM(P=1:5) DPRT(3,2,P) * X(P,4) &
                             + SUM(P=1:5) DPRT(3,2,P) * X(P,6) &
                             + SUM(P=1:5) DPRT(3,2,P) * X(P,8) - KRT(3,2)*M(3,2) < 0
!
DEMAND(P=1:5):               SUM(S=1:8) X(P,S) < MD(P) * Y(P)
!
RSUSVAR(R=1:3,T=1:2):        M(R,T) -  MAXRES * YM(R,T) < 0
!
RESTYPE(R=1:3):              YM(R,1) + YM(R,2) = 1
!
MEXPROD1:                    Y(1) + Y(2) < 1
!
MEXPROD2:                    Y(3) + Y(4) < 1
!
```

```
BOUNDS                          ! DEFINING BINARY & INTEGER VARIABLES
!
X(P=1:5,S=1:8).PI.30
M(R=1:3,T=1:2).UI.MAXRES
Y(P=1:5).BV.
YM(R=1:3,T=1:2).BV.
!
GENERATE
```

APPENDIX C

SEDE 1.0 USER'S GUIDE

SEDE 1.0 is an integrated software application package for simultaneous engineering design evaluation. It utilizes the linear mixed integer design evaluation model developed in this thesis to evaluate candidate design configurations generated as a result of simultaneous engineering design activity.

SEDE 1.0 integrates two existing copyright protected software packages; Paradox 3.5 for DOS, a relational database management system, and XPRESS-MP, a linear and integer programming modeling language and solver. Duplication and distribution of SEDE 1.0 may be a violation of the copyright law.

SEDE 1.0 runs on IBM or IBM compatible personal computers using the DOS operating system. To start SEDE 1.0, make the SEDE directory the current directory and type SEDE at the prompt. Example: C:\SEDE>SEDE.

The following screen will appear:

```
              SIMULTANEOUS ENGINEERING DESIGN EVALUATION


     1.     EDIT INPUT DATA IN PARADOX TABLES
     2.     GENERATE INPUT MATRIX
     3.     GENERATE OPTIMAL INTEGER SOLUTION
     4.     READ RESULTS
     5.     QUIT


     Type the number you want and press ENTER:
```

Choose menu choice 1 to execute Paradox to enter or edit model input data. Model input parameters are stored in four Paradox tables namely Table 1 through Table 4. Data values can be input or updated in one or all tables sequentially using menu driven Paradox commands. Data values for the model can be printed for future reference using the print command.

Choose menu choice 2 to generate the model input matrix file, SEDE.MAT. Menu choice 2 directs XPRESS-MP to read the design evaluation model file, SEDE.MOD, and the data values for the model parameters from Tables 1 through Table 4 to generate the model matrix file.

Choose menu choice 3 to generate the optimal solution. Menu choice 3 directs XPRESS-MP to search for an optimal integer solution. XPRESS-MP reads the matrix file and determines the optimal integer solution. The optimal solution is then stored in an ASCII file called SEDE.PRT.

Choose menu choice 4 to read and print, if desired, the output file. The output file contains optimal values for the objective function, model decision variables and also slack values for analysis.

Choose menu choice 5 to quit and return to DOS.

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