AN ECONOMIC EQUIPMENT REPLACEMENT MODEL
FOR
FLEXIBLE MANUFACTURING SYSTEMS

by

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ABSTRACT

This dissertation develops an economic equipment replacement model suitable for Flexible Manufacturing Systems (FMSs). An FMS represents an integrated machining system which produces multiple products and utilizes multiple inputs including avital materials handling system. The system's interactive nature defies traditional replacement works which are confied to one-for-one as well as like-for-like situations. The model developed in this work addresses the issue of multiple machine replacement. Considerations incorporated include layout, transportation, materials handling capacity, flexibility, capacity expansion/contraction, obsolescence and deterioration, inputs substitution, and equipment depreciation. This model is demand driven. The optimality criterion is the maximization of the after-tax future worth of the system at the end of a specified planning horizon. The 1983 ACRS rules are used. Illustrative examples are provided throughout.

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CHAPTER I

INTRODUCTION

The objective of this research is to develop an equipment replacement model suitable for Flexible Manufacturing Systems (FMS). FMSs have received considerable attention in the manufacturing sector in the past few years. They have been highly acclaimed for their potential to improve productivity for medium volume production. However, a formal economic replacement evaluation for an FMS has never been published. Existing equipment replacement models fail to capture the characteristics of an FMS. This research addresses specific issues related to the complex nature of these systems.

The remainder of this chapter is organized as follows: the physical characteristics of an FMS are described first. Then, the needs for replacement analysis in the context of an FMS are discussed. The final section outlines the specific objectives for the proposed research.

I.1 DEFINITION OF FLEXIBLE MANUFACTURING SYSTEM (FMS)

As suggested by the Charles Stark Draper Laboratory [1], a Flexible Manufacturing System can be defined as:

> "A computer-controlled configuration consisting of semi-independent work stations and a material handling system designed to manufacture more than one part number at low to medium volumes."

The benefits of automation in continuous, high-volume production has been well documented. For low to medium volume production, however, an FMS is an alternative to traditional systems where the potential for dramatic increases in productivity may be achieved. An FMS aims to automate production of families of parts in a batch manufacturing environment. It utilizes computer-controlled material handling systems to forge a link between machine centers. The essential components of an FMS are:

(a) potentially independent numerical control machines,

(b) a material handling system to handle parts between machine centers, and to-and-from load stations, and

(c) a system control design which co-ordinates the machine tools, the conveyance system and the work pieces.

Additionally, work-in-process and tooling requirements can be satisfied by interfacing an automated storage and retrieval system with the other segments of the manufacturing operations.

I.2 ADVANTAGES OF AN FMS

It has been suggested that an FMS allows the efficiency of automation without sacrificing flexibility; this assessment is particularly valid for medium level production. That is, the flexible nature of the system allows both production of a variety of parts and a quick response to varying production requirements. The fixed cost of the system is spread over many more part types. The system can easily adapt to fluctuating demand, new product designs, engineering changes, etc.

Other benefits attributed to automated operation include:

(a) parts of high and uniformly consistent quality,

(b) dramatic labor reduction,

(c) reduced inventory level,

(d) shorter manufacturing cycle times, and

(e) better machine utilization.

I.3 HIERARCHICAL CONTROL OF FMS

An FMS typically consists of four levels of decisions (see Figure I.1):

Level 1 - batching strategy,

Level 2 - part and tool allocation,

Level 3 - operator control, and

Level 4 - computer control.

At the top level, the production requirement for the FMS over some period of time is specified. Part batching strategies are determined at this level in order to satisfy such constraints as tool capacity and due date requirements. At the next level, detailed assignment of parts and tools to machines are made for each batch. Here, allocation constraints would include in-process inventory, workload on FMS, machine failure, fixture constraints, tool capacity and tool costs. At level three, the operator interfaces with the computer-based control system. He is given a number of controls to coordinate the system performance. In general, these control parameters include (a) the total number of pallets in the system, (b) the total number for each pallet type, and (c) the specification of part priorities. The fourth level deals with the numerous decisions which are normally under computer control. These

	Decisions
Level 1	Batching Strategy -Which parts to produce during which time period.
Level 2	Part and Tool Allocation -Assignments of parts to machine. -Assignments of tools to machine.
Level 3	Operator Control -Total number of each pallet type in system. -Part priorities and other control parameters.
Level 4	Computer Control -Part input sequence. -Next machine to process a part. -Next cart to transport a part. -Routing of part between machine.

Figure I.1.

Hierarchical Control of FMS

decisions include control of the material handling system, routes of parts to the proper machines, etc.

I.4 PERFORMANCE EVALUATION OF FMS

The operational performance of an FMS can be measured relative to the following objectives:

(i) to meet due date,
(ii) minimization of time required to process all parts,
(iii) maximization of machine utilization,
(iv) minimization of in-process inventory, and
(v) minimization of material handling system usage.

The list is in no way complete nor are these objectives necessarily compatible. In fact, it is common to find decisions which place high priority on one objective at the expense of another. Obviously, the analysis would be much simpler if these objectives could be measured in comparable monetary values.

I.5 TYPES OF FMS

The effectiveness of an FMS depends on many factors including part characteristics, material, size, accuracy, and processing requirements. Table I.1 shows a general relationship between several types of manufacturing systems and production requirements for each part. Transfer lines represent the most efficient method for high volume sequential operation, particularly for the production of a very small variety of parts. However, its versatility is limited because of the tooling and setup required. Independent numerically controlled

Table I.1

General Relationship Between Several Types of Manufacturing Systems and Production Requirements for Each Part [2].

Type of Manufacturing System and Degree of Flexibility	Number of Parts in Family	Average Quantity per batch
LOW		
Transfer Line	1 - 2	7,000 and up
MEDIUM		
Dedicated FMS	3 - 10	1,000 - 10,000
Sequential or Random FMS	4 - 10	50 - 2,000
Manufacturing Cell	30 - 500	20 - 500
HIGH		
Stand-Alone NC Machine	200 and up	1 - 50

machines, on the other hand, are more suitable for the production of a variety of parts because of greater versatility for part change. Their efficiency, however, is relatively low. An FMS can be effective in the midrange production levels where three to a few hundred part types are produced in batches of under 100 units.

There are several ways of configuring an FMS, each resulting in various degrees of flexibility:

(i) manufacturing cells,
(ii) random or sequential systems, and
(iii) dedicated systems.

I.5.1 Manufacturing Cells

Typically, manufacturing cells consist of clusters of numerically controlled machines served by a robot. It is also possible to integrate a sequence of clusters into multi-cluster systems.

I.5.2 Random Operation and Sequential Operation

A sequential system follows a sequential flow pattern to produce one batch of parts after another; this system is characterized by quick tool-change capability to accommodate a family of parts. In random systems, several different parts may be worked on simultaneously by versatile machines. The layout configuration becomes important for routing parts to selected machines.

I.5.3 Dedicated Systems

Dedicated systems often include specialized machines, dedicated to a narrow range of heavy bulky parts.

I.6 MATERIAL HANDLING DEVICES FOR DIFFERENT TYPES OF FMS

Effective operation of an FMS requires that the material handling devices and machining operations be coordinated, under a hierarchical control system monitored by a computer. With respect to the handling method, there are two categories of parts handled: (a) parts of rotation such as cylinders, gears, etc., and (b) prismatic parts.

Rotational parts, in general, require turning operations. Since they are usually within the weight limit of robots, they are often transferred by robots. They can be carried, in multiples, as a unit load on special delivery pallets which are designed for pickup by robots. Prismatic parts, however, are often too heavy for robots to handle. They are normally clamped to fixtures on metal machining pallets which are designed to fit on the bed of the machine tool. Various kinds of mechanisms are used to transfer these pallets. Typical material handling equipment used for delivering parts in typical FMS layouts is listed in Table I.2.

I.6.1 In Manufacturing Cells

Robots are utilized to handle individual parts. Coordination of robot moves according to the changing requirements of the machines are commonly performed by microprocessors. Also, buffer storage required to maintain continuous machining operations needs to be considered. In many FMSs, buffer storage is provided at the machine on conveyor spurs

Table 2

Characteristics of Materials Handling Equipment for Deliverying Parts in Typical FMS Layout [3].

	Part weight carried-low to very high	Uses parts-orienting pallets	Uses machining pallets	Structure on floor	Straight-line layout-sequential stations	Straight-line shuttle-machines both sides	Narrow-loop layout-machines both sides	Wide-loop layout-machines at center	Self-powered carrier	Self-loading carrier	Link to central storage	For overhead central storage	Flexibility for layout change
DEDICATED MFS - Heaviest parts: 40,000 lb													
Self-powered shuttle cars	Very High		✓	✓		✓			✓	✓			
SEQUENTIAL OR RANDOM FMS - Heaviest parts: about 8,000 lb													
Powered roller conveyor	High		✓	✓			✓	✓					
Towline conveyor	High	✓	✓					✓			✓		
Car-on track conveyor	Medium	✓	✓	✓		✓	✓						
Wire-guided vehicles	Medium	✓	✓					✓	✓	✓	✓		✓
AS/RS machine	Medium	✓	✓	✓		✓			✓	✓	✓		
Power and free conveyor	Low	✓									✓	✓	✓
Powered monorail carrier	Low	✓									✓		✓
MANUFACTURING CELL - Heaviest parts: about 200 lb													
Gravity tracks and storage towers	Low	✓		✓	✓								
Powered roller conveyor	Low	✓		✓	✓								
Customized metal belt conveyor	Low			✓	✓								
Powered monorail carrier	Low	✓									✓		✓

or in pallet exhange transfer mechanisms. In other systems, storage is provided by conveyor systems between machines, or at a parts set-up area before or after palletizing.

I.6.2 In Sequential or Random FMS

The transfer capability is often decentralized at the machine tool level. That is, at each machining station, pallet transfer mechanisms move machine pallets between the delivery equipment and the beds of machine tools.

I.6.3 In Dedicated FMS

Centralized transfer capability is commonly found within the delivery system. For example, on-board powered transfers are provided on self-powered carts that ride on rails and carry heavy loads between machine tools.

I.7 NEEDS OF FMS REPLACEMENT ANALYSIS

As presented in the preceding sections, an FMS represent a manufacturing system which has great potential to improve productivity through the integration of computers, material handling systems, and production equipment. In the past ten years, a few such systems FMS have been installed (see Appendix I). In the very near future, the productivity of FMSs needs to be assessed with respect to their continual deterioration and the changing external environment brought about by newer, and technologically superior machines. Their courses of action include upgrading the FMS components, replacing or adding FMS components, or even replacing the entire FMS. The need for an FMS replacement strategy is apparent. However, the problem of "replacement" in an FMS environment has not received much attention.

Theoretical work on equipment replacement decision has its origin in the works of Taylor [4] and Hotelling [5] in the 1920's. Many works have since been published, notably the contributions made by Terborgh [6,7,8]. While these earlier works enlightened our understanding of the economic nature of replacement decision, they lack depth in characterizing the production environment against which such decisions are currently made. The MAPI formula [6,7,8], for example, represents the most popular evaluation procedure to date. Its effectiveness, however, remains questionable. As recent as September 1981, the SME--Manufacturing Engineering Education Foundation voiced the following skepticism:

> "It is a major concern that manufacturing productivity has been blunted by the machine justification procedures (MAPI formula) used in most American companies [9]."

The ineffectiveness of using existing replacement models to analyze an FMS can be attributed to the many simplistic assumptions underlying these models. Frequently encountered are such assumptions as like-for-like, infinite horizon, single machines, etc., all of which are inadequate for the complex FMS production environment. From a production planning standpoint, an FMS possesses the following characteristics:

(i) multiple machine stations,

(ii) multiple products,

(iii) interrelated activities, and

(iv) initial inputs, and intermediate and final products.

Should a decision maker be faced with the problem of replacing the whole FMS, then it seems appropriate to view the entire unit as a single machine and the analysis could proceed as such. Under this scenario, existing models for single machine replacement could possibly be applied. However, if the problem involves replacement of a particular machine station within the FMS, then one could envision the inadequacy of the single machine model; for the replacement of one machine affects the operation of the entire system. That is, it raises regarding the input/output requirement of other machine stations, sequencing of production activities, machine utilization, machine capacity, and most importantly, the flexibility of the entire FMS.

The foregoing discussion outlines both the need for FMS replacement analysis and the need to develop a more comprehensive replacement model suitable for the FMS environment. The section to follow outlines the objectives of the research proposed for the dissertation.

I.8 RESEARCH OBJECTIVES

The ability of a system to accommodate different levels of capital intensiveness is directly proportional to the system's ability to expand or contract, to economically utilize inputs, and to produce new products. It is the intention of this research to capture these elements in a multi-machine, multi-product setting, as in an FMS system. Specifically, this research will attempt to develop a replacement model suitable for an FMS. Special attention will be given to the following considerations:

(i) input substitution,

(ii) machine utilization,

(iii) interrelated activities, and

(iv) capacity expansion/contraction.

The economic criterion will be the maximization of terminal worth of the system at the end of a specified planning horizon. Allocation considerations will include labor, and material.

In summary, the general characteristics of Flexible Manufacturing Systems have been described. The purpose is to identify the general characteristics and structure of an FMS. Also, the objectives of the proposed research has been stated. In Chapter II, the relevant topics of equipment replacement are discussed. It is intended to introduce the fundamentals of replacement problems. Chapter III provides a detailed discussion of the factors considered in replacement studies. The many considerations vital to replacement analysis are highlighted in this chapter.

Chapter IV surveys the literature on replacement economics beginning from its origin in the 1920's to the present period. Relevant issues related to the research are discussed. Chapter V places an FMS in the context of a replacement analysis. Many significant considerations are identified. Chapter VI provides the model formulation. Here, a multi-year replacement model is developed; the formulation is one of dynamic programming. Chapter VII examines the parts assignment problem which is a sub-problem within the multi-year replacement model. Chapter VIII extends the parts assignment problem to a replacement content. And in Chapter IX, the multi-year replacement model is illustrated. Throughout Chapters VII, VIII and IX, the same example is used to illustrate and highlight the relevant concepts. Chapter X summarizes this research.

CHAPTER II

GENERAL REPLACEMENT TOPICS

This chapter outlines the general nature of replacement economics. The discussions include the definition of replacement, reasons for replacement, types of replacement, and performance measures used in replacement studies. The relevance of these topics to the FMS replacement problem is assessed.

II.1 DEFINITION OF REPLACEMENT

There are numerous ways of defining equipment replacement. Ray gives the following definition:

> "In general, and in the most liberal interpretation it means that a system, be it an entire process, a machine or component, has been displaced from service. There is no implication of functional demise, nor of the dissolution of ownership, but merely the fact that the system has been displaced from its past position of rendering service for economic or utility reasons [10]."

Terborgh, perhaps the most significant contributor in this area, refers to the nature of replacement studies in the following quote:

> "It follows that replacement policy is much broader than acquisition policy. Its task is not simply the procurement of new facilities which can economically take over the functions of existing equipment, it is the assignment of existing equipment itself to secure the highest service at the lowest cost.

> Replacement policy should insure that all facilities in service are able to defend their function against economical displacement by any challenger whether inside or outside the same ownership [6]."

In simplistic terms, equipment replacement policy principally addresses two issues: when to replace and with what.

II.2 REASONS FOR REPLACEMENT

Reasons for replacement are many. In a manufacturing environment such as FMS, there are five major reasons:

(a) Physical Impairment
(b) Obsolescence
(c) Capacity Expansion/Contraction
(d) Input Allocation
(e) Product Substitution

II.2.1 Physical Impairment

Physical impairment refers to changes in the physical condition of the asset. Machines deteriorate as they age over time, operate less efficiently, and require increased demand for maintenance.

II.2.2 Obsolescence

Obsolescence describes the effects of changes in exogenous factors as a result of continuous technological improvement of the production equipment. New and improved machine designs may render an existing piece of equipment both technologically and economically obsolete. Often, the rate of such improvement is so great that replacing a physical asset in good operating condition with an improved unit could result in attractive savings.

II.2.3 Capacity Expansion/Contraction

Increased demand for existing products may render a present machine inadequate to meet a desired production output. Hence, an equipment item with higher capacity may be desired. Conversely, the demand for machine activity may have declined to a point where it becomes more advantageous to replace it with a piece of equipment of lower capacity.

II.2.4 Input Allocation

The cost of a production system depends upon the value of inputs and the level of consumption of these inputs. Thus, an alternative production system could prove to be economically superior if it could better utilize inputs of lower cost. An obvious case is the substitution of a labor intensive production system by a capital intensive one or vice versa. As more and more automated systems become available, the consideration of capital-labor substitution can no longer be ignored.

II.2.5 Product Substitution

The survival of a firm largely depends on the environment within which the system operates. Due to rapid technological changes and fierce market competition, many firms need to change or modify their products. As a result, the production system might need modifications to adjust to new product changes.

II.3 TYPES OF REPLACEMENT SITUATIONS

In general, replacement problems can be classified into three categories:

(a) items that physically fail suddenly,

(b) items that lose their value suddenly due to instant obsolescence, and

(c) items which deteriorate and become obsolete with time.

II.3.1 Items that Fail Suddenly

This problem has led to the development of the study area of reliability. Reliability deals with the development of policies and procedures to determine the tradeoffs between equipment and installation costs, and the cost of lost service.

II.3.2 Items Subject to Instant Obsolescence

Here, the concern is with instant obsolescence (Military aircraft normally experience this type of replacement). Electronic computers in the business world would be a close analogy to military aircraft in national defense. The idea is that once the unit has become obsolete it has lost its value. Thus, production or acquisition of the item is terminated.

II.3.3 Items Which Deteriorate and Become Obsolete With Time

This is perhaps the most common replacement situation and the one which has the greatest effect on the productivity of most production systems. The continual deterioration of the existing machine coupled with advances in the state-of-art of equipment design warrants the replacement of the old equipment.

A special case of this situation is when equipment is replaced by an identical unit, i.e. like-for-like replacement. Like-for-like replacement is practically nonexistent and its main use is, at best, a philosophical one.

II.4 PERFORMANCE MEASURES OF REPLACEMENT

Past studies on replacement have originated from such diverse groups as mathematicians, engineers, operation researchers, business administrators, economists, etc. Although their approaches and emphases have been diversified, their objectives were often the same: to determine the optimal replacement policy -- when to replace and what to replace by.

The determination of an optimal equipment replacement policy involves both economic and non-economic factors. Historically, the primary economic criterion is the minimization of capitalized and maintenance costs. Obsolescence and deterioration are incorporated into the machine cost function. Discounted cash flow methods (e.g. present worth, rate of return, etc.) have been widely applied as the measure of economic performance of a replacement policy.

However, minimization of costs as an objective implicitly assumes that the revenue component is constant. That is, the revenue effect which can be attributed to the production system will not be altered in anyway by the new system. If replacements alter the revenue structure within the planning horizon, then the maximization of profit is necessary.

Alternatively, or in conjunction with economic criteria, non-economic performance measures are also applied. Depending on the emphasis of the institution involved, such measures could range from the system's ability to kill as in the military to its ability to save as in the hospital. In an FMS environment, commonly encountered measures include machine utilization, reliability, scheduling performance, in-process inventory, etc. Although not expressed in terms of actual dollars, these utility measures could indeed be economically motivated.

II.5 DISCUSSION

In this chapter, the conceptual nature of economic replacement has been outlined. An FMS, like many other manufacturing systems, is subject to deterioration and obsolescence. Its replacement policy lies with the system's ability to expand or contract, to adjust to changes in product design and product mix, and to efficiently allocate inputs. The next chapter will discuss the major considerations involved in replacement analysis.

CHAPTER III

MAJOR CONSIDERATIONS IN REPLACEMENT STUDIES

The preceding chapter introduced the conceptual aspect of replacement. For an FMS decision maker to select a good replacement policy, he/she has to incorporate all the major considerations relevant to the system's environment. Considerations such as choice of criterion, product price-volume relationship, selection of production technology, selection of a planning horizon, capital budgeting, tax, and information gathering are all vital elements of the replacement process. This chapter will highlight these elements individually. It is intended to focus on their impact upon the FMS replacement decision.

III.1 CHOICE OF CRITERION

As discussed previously, performance measures can either be economic or non-economic. The present work will solely address the economic performance of a replacement policy. There are two commonly employed criteria: cost minimization and profit maximization. Cost minimization involves the minimization of aggregated discounted value of the initial investment, salvage value and operating costs of the machine. The profit maximization criterion includes the revenue component. The two criteria are unique but could be equivalent under certain conditions. In general, if the revenue effect is constant with respect to quantity produced, then cost minimization is in effect identical to profit maximization. Analytical models whose output level is fixed fall under this category. This implicitly assumes no expansion. The validity of applying either criterion depends largely upon the price-volume relationship of the product's economic market place. Thus, if the revenue effect can be assumed to remain constant for all replacement alternatives, then the replacement decision can only be influenced by the relevant cost considerations. Otherwise, cost consideration alone would not be sufficient.

It should also be identified that there exist different forms of cost minimization and profit maximization as well. Namely, minimization of unit cost, minimization of total cost and maximization of unit profit, maximization of total profit. Their expositions and implications can be found in Leung [11] and is omitted here.

III.2 CONSIDERATIONS FOR CAPACITY EXPANSION OR CONTRACTION

When a replacement activity does not correspond to a change in output level as in the case of like-for-like replacement, it can be viewed as replacement without expansion/contraction. It follows then that when an increase/decrease in the output level is brought about by virtue of replacement, such can be viewed as replacement with expansion/contraction. In fact, a primary motivation for replacing an existing machine may be to realize an increase in profit by decreasing product selling price which could in turn increase the product demand, which in turn warrants a machine of higher capacity.

Henceforth, in order for a firm to evaluate the viability of capacity expansion, it is crucial that the firm accesses the price-volume relationship for all its products for each individual time period within the firm's planning horizon. Naturally, an effective policy should have the capability to identify the output level at which the equipment operates.

III.3 SELECTION OF PRODUCTION TECHNOLOGY

The choice of production technology directly affects the utilization of inputs. For example, relative to a manual system, an automated system requires more skilled labor, less unskilled labor, more capital, and perhaps more supporting units. In times where skilled labor is cheap, unskilled labor expensive, and capital abundant, acquisition of an automated system is a logical investment. Another advantage offered by automated systems is that of economies of scale. That is, the ability for automated systems to produce in very large quantity enables the average cost of manufacture to decrease. However, if output level is low, unit cost could be relatively high due to higher set-up cost. Clearly, here is a case of tradeoffs between higher set-up costs and lower variable cost.

In general terms, capital and labor intensiveness represent two extremes of production technology. Very often, a labor-intensive system is preferred when output level is low, and becomes relatively less desirable as the quantity of production increases. Indeed, if the system has the flexibility to adapt to different levels of capital-labor intensiveness, it already has a vital element in keeping cost down.

III.4 SELECTION OF A PLANNING HORIZON

Analysis of replacement decisions cannot be complete without a proper selection of planning horizon. The choice of planning horizon has been arbitrary. The assumption of infinite planning horizon is common among analytical models that have appeared in academic journals. In certain cases, this assumption is questionable. For example, the joint assumption of infinite planning horizon and like-for-like replacement is likely to be weak. For it is difficult to expect a production system to continue utilizing the same production technology over an infinite period. Perhaps such an assumption eliminates computational difficulties and is indeed valid given the model environment; it is however limited in its application. In practice, the planning horizon is often finite, especially among manufacturing firms.

Thus, the assumption of an infinite planning horizon remains a philosophical one. Its value in application is limited, particularly in the business world. In addition, the further one forecasts the less accurate it becomes. For the present work, since the environment is manufacturing, a finite horizon will be used.

III.5 CAPITAL BUDGETING CONSIDERATIONS

Similar to any project selection process, equipment replacement is subject to capital rationing criteria. Capital rationing refers to the restriction on funds for investment because of limitations imposed either (a) by management or (b) by the capital market. The former could be termed as internal capital rationing, where management decides to limit the total amount of funds available for capital expenditures to a fixed amount in a given period or management establishes a cutoff rate which measures the "attractiveness" of individual alternative. The latter could be termed as external capital rationing, where the firm cannot obtain funds from the capital market in sufficient amount at a price the firm considers economical.

In most equipment replacement decisions, particularly in the manufacturing sector, the budgetary considerations often correspond to internal capital rationing.

III.6 RATE OF DETERIORATION AND RATE OF OBSOLESCENCE

Deterioration implies that the efficiency of an existing machine decreases with time. Such a phenomenon is due to the physical impairment of the system. As a result, the system continually requires more and more inputs while producing the same amount of output. In a manufacturing context, this could mean a gradual increase of the following inputs: direct labor, energy consumption, raw material, maintenance labor, supporting unit, etc. Here, the concern is the rate at which the system is deteriorating. There appears to be no other simple way to assess the system's deterioration rate other than keeping historical record and extrapolating certain patterns therefrom. Nevertheless, assumptions of a linearly decreasing rate or an exponentially decreasing rate are common.

Obsolescence occurs completely external to the firm. The obsolescence rate is the rate at which the state-of-art of the equipment design improves. Indeed, forecasting technological change is a discipline in itself; and the determination of an obsolescence rate remains an extremely difficult task. Again, making use of historical data seems viable. Assumptions of linear and exponential rates are common.

III.7 TAX CONSIDERATIONS

The economic merit of a replacement policy cannot be accurately evaluated without consideration of the effects of taxes. According to the latest Economic Tax Recovery Act [12], there are five classes of tangible assets and the tax year for each individual class is fixed. A comprehensive exposition can be found in Blank et. al. [13]. The historic background, features relative to proposed project analysis, and advantages of the new system from a tax viewpoint are discussed in this reference.

III.8 PROBLEMS WITH INFORMATION GATHERING

In order to obtain a good replacement policy, it is important that the replacement model be appropriate to the situation where it is applied. Also of vital importance is the accuracy of information which the model requires. In replacement analysis, information gathering often presents a major problem. A good replacement policy should incorporate considerations for future changes. Within the firm, this would mean estimates on future machine prices, machine salvage value, labor and material costs, demand change, capital expenditures, etc. In many cases, a good forecasting mechanism is warranted and a good data structure is necessary to detect these changes. Inevitably, an element of error is inherent. Naturally, the further one looks into the future, the less accurate the information becomes. The problem is even more complicated when external information is required. A replacement policy cannot be complete without considerations of both the state-of-art of production technology and the way the technology is changing. This implies an assessment on technological change and that is a complex issue by itself. The problems associated with information gathering can impede the implementation of an effective replacement policy and can result in inaccurate decisions.

CHAPTER IV

SURVEY OF LITERATURE ON REPLACEMENT

IV.1 CONCEPTUAL DEVELOPMENT

IV.1.1 Origin of Economic Life

Modern equipment replacement analysis has its origin in 1920 in the articles by Taylor [4] and Hotelling [5]. Taylor developed a mathematical expression for the average unit cost of a machine over a variable time period of service. He showed how this period of service can be determined such that the unit cost of production is at a minimum. This period of service is termed the economic life of the machine. From the criterion of cost minimization, Hotelling generalized it to profit maximization. He introduced the criterion of maximizing the present value of the machine's revenue minus its operating and capitalized costs within the machine's economic life.

IV.1.2 Replacement Chain

In 1940, Preinreich [14] showed that the economic life of a single machine could not be determined independent of the economic life of each machine in the chain of future replacements. Similar to that of Hotelling's, his criterion is: maximization of the present value of the earnings of future replacements minus the present value of the costs of all these machines. Along with the assumption that the planning horizon is infinite, the model developed assumes that all machines in the replacement horizon, i.e. the replacement chain, are identical.

Although Preinreich's model is simplistic, the concept of a replacement chain represents a major milestone in the development of replacement economics. Thereafter, all replacement models proposed recognize this "chain" effect.

IV.1.3 Obsolescence and Deterioration, MAPI Methods

In 1949, Terborgh [6] provided another milestone in the replacement field. He extended Preinreich's work to account for equipment obsolescence. Terborgh contended that the replacement of an existing machine should be conditioned by a comparison of its performance with that of the latest new equipment. Here, Terborgh introduced two new terms which have since been popularized: (i) defender -the existing old asset and (ii) challenger -the latest equipment being considered. The innovative idea is that the growth in the inferiority of the defender relative to the initial performance of the challenger is the key factor which warrants replacement. Terborgh's inferiority growth factor consists of two components: obsolescence and deterioration.

Other related works of Terborgh have been published since 1949 [7,8], better known as the MAPI methods. These later works extended the principles of the original work to other types of investments. The basis of these MAPI methods is a rate-of-return analysis computed from the annual equivalent cost, when equipment is held for one more year. More appropriately, the "rate-of-return" is an "urgency rating" [15]. Both the opportunity costs and costs of delay are taken into account. The MAPI methods are oriented towards practitioners in industry. As such, considerable attention is given to such elements as income tax, depreciation schedule, income patterns, and various rates of "inferiority growth" rates.

IV.1.4 Production Function Approach

In 1967, Smith [16] formulated a replacement model within the framework of production theory. Using input-output production concepts, he expressed the cost of a production system as a function of the replacement intervals in the replacement chain. Examining replacement problems utilizing production functions enables one to investigate the effect of both input substitutions and capacity expansion. Similar approach can be found in Caracostas [31] where production economics theory is applied to the selection ship containers.

Leung and Tanchoco [17] later extended Smith's work to include such factors as input substitution, expansion of output and product price-volume relationship. The optimal replacement policy would maximize the production process terminal wealth over a finite planning horizon.

IV.2 ECONOMIC INTERPRETATIONS

Many works on replacement economics have also appeared in the microeconomic literature: Alchian [18], Williamson [19], Swan [20], Verheyen [21], and Smith [16]. There are three major interpretations: (i) Labor-saving technological change, (ii) replacement interval, and (iii) profit maximization versus cost minimization.

IV.2.1 On Labor-Saving Technology Change

Swan's model captures the essence of replacement with labor-saving technological change. He shows that the age at replacement of a chain of machines is continually rising over time and that a rise in wage rate or fall in the machine price increases optimum lives. An infinite planning horizon is assumed in his model.

IV.2.2 On Replacement Interval

Verheyen concludes that the moment of replacement is always determined by the equality of marginal replacement costs to the marginal costs of postponed replacement. On the assumption of equidistant replacement, Smith asserted that in the face of steady technological improvement in equipment, the economic life of equipment would not change abruptly from one replacement to another.

IV.2.3 On Profit Maximization vs Cost Minimization

In [16], Smith attempted to clarify the relationships among profit maximization, cost minimization, capacity expansion, and price policy. He pointed out that an optimal replacement policy cannot be determined independently of output and therefore price policy. In addition, he concluded that in the absence of technological change, a cost minimization policy is equivalent to a profit maximizing replacement policy. This preceding generalization however is limited by his assumptions of equidistant replacement and a product output policy at the replacement point, a policy that is maintained over the life of that equipment.

IV.3 MATHEMATICAL PROGRAMMING MODELS

IV.3.1 Dynamic Programming Formulation

Due to the combinatorial nature of replacement problems, many mathematical programming formulations have resulted. The problem was first formulated in 1955 as a dynamic programming model by Bellman [22] and later advanced by Dreyfus [23]. They assume exponential functions for both maintainance costs and capitalized replacement cost. Indeed, not only does dynamic programming provide a convenient computational procedure, it also depicts the structure of replacement problems.

Similar discussions can be found in two separate works by Wagner [24], Dreyfus and Law [25]; the dynamic replacement model is described as a network. In 1981, Oakford et. al [26] provided a similar dynamic framework with extension to incorporate several challengers. The authors outlined a good structure; however, the assumption of identical machine replacing itself was still embraced.

IV.3.2 Allocation Considerations

Utilizing mathematical programming models, many works have been developed incorporating a multitude of allocation constraints. Three relevant areas are discussed below:

(i) On capital budgeting: Shore [27] argues that Terborgh's method might be an appropriate strategy if the firm had an unlimited supply of funds. He raises the issue that a replacement project could in fact be one of the many investment alternatives competing for limited funds. With this resource allocation orientation, equipment replacement is cast as a capital budgeting problem utilizing Weingartner's model [28]. Shore's paper presents a scheme for developing benefit-cost ratios so that the productivity of potential replacement can be measured.

(ii) On expansion: Focusing on the expansion aspect of a plant investment, Philip et. al [29] develops a non-linear programming model to determine the initial size and expansion policy for a plant investment assuming a finite horizon. Their model however, assumes that replacements of existing equipment are treated independent of future expansions.

(iii) On multiple machines: Hannssmann [30] considers replacement of machines which are either in series or in parallel. Although simplistic in many aspects, budgetary and expansionary considerations are incorporated. Hannssmann's work represents one of the earliest works on the subject of multiple machine replacement. Ray [10] expanded on this "system approach" concept and modeled the replacement problem as a network of interacting components. His general model is formulated as a mixed zero-one programming model with a finite planning horizon.

IV.4 DISCUSSION

This chapter has presented a comprehensive review of the major works in replacement theory. Applications of replacement models have been documented: Kamerich et. al. [32], Eilon et. al [33], and Peterson [34]. All these applications involve replacement of either single machine or single production system. In fact, except for the works of Hannssman and Ray, the theoretic works thus far have paid little attention to the multiple machine case. While Hannssmann's model is overly simplistic, Ray's work does not incorporate many of the major considerations.

A Flexible Manufacturing System represents a multi-machine multi-product environment. It is characterized by interrelated activites, with output at one machine being input to another. Changes in one machine could well affect the productivities of other machines and hence the whole FMS. Thus, the replacement policy of an FMS component cannot be examined independently of other components in the system.

CHAPTER V

THE FMS REPLACEMENT ENVIRONMENT

V.1 INTRODUCTION

Traditional replacement situations involve the evaluation of machines which can be viewed as independent units. An FMS represents a multi-machine environment where changes in one machine could well affect the performance of other machines in the system. As such, even if only a single machine is being considered for replacement, the replacement analysis needs to be extended to the whole FMS arena. For example, it is conceivable that while one machine is preferred to another when operated individually, it could result in a poorer overall system performance. In essence, no longer can machines be viewed as independent units but as interacting components of a much larger system. With these integrations in mind, this chapter will outline the major issues involved in the replacement of machines in an FMS. Such issues include assignment of machining parts, transportation cost, layout problems, machine flexibility, and machine capacity. The intent is to set the perspective for the multi-machine replacement model formulation to follow.

V.2 ASSIGNMENT OF MACHINING PARTS

In an FMS, machine parts are assigned to individual machines for either a single machining operation or a sequence of operations. The assignment process usually takes place periodically and is generally motivated by workload changes and/or machine utilization improvements.

In fact, a frequent update of machine assignment is relevant to the efficient use of the entire system. For instance, faster deterioration rate for certain machines (old ones in particular) could render a previously desirable parts assignment undesirable.

In the case of replacement evaluation, an appropriate assignment of machining parts needs to be performed for both the incumbents and challengers. For example, consider the situation where one of the machines in the FMS is considered for replacement. Assume that the challenger is of identical type to the defender; this challenger, being more technologically updated and free from wear and tear, can handle more workload than the defender. Moreover, if the challenger is a different machine type which can perform a greater variety of operations, then the reassignment of parts to machines becomes even more important. This is an issue of system flexibility and will be discussed in the following section.

V.2.1 Machine Flexibility

As discussed in the preceding section, if the challenger can perform a greater variety of operations more efficiently than the defender, then a reassignment of parts to machines is necessary in order to take advantage of the capabilities of the challenger. For example, if a milling machine is displaced by a general purpose machining unit, then it is conceivable that this new unit could pick up some parts which were previously assigned to other machines. The issue here is flexibility. Suppose that a firm is considering two challengers, one with feature identical to the incumbent, while the other includes additional features. How then should these challengers be compared? The obvious issue is whether the additional flexibility justifies the extra investemnt. And, the merit or demerit of this additional flexibility can be reflected by the additional savings or cost of the FMS after machining parts have been reassigned. Clearly, if the overall savings is less than the incremental investment, then the additional flexibility is not desirable. The converse also applies. It should be noted that such economic analysis needs to be performed over the entire planning horizon.

Another important aspect of this flexibility issue involves the effects of changes in product mix as well as product demand. If the FMS is operating in a product environment where changes in product mix are frequent, then the merit of such added flexibility should prove to be significant. Similarly, if the product demand fluctuates drastically, then the flexibility feature enables quick response for workload distributions; with a special purpose machine, this would not be possible. Thus, for an FMS environment, the evaluation of machine flexibility needs to incorporate the parts assignment decision.

V.2.2 Transportation Costs vs Machine Costs

In traditional single machine replacement, because of the assumption of independent machine units, the issue of transporation is often omitted. In an FMS environment, transportation cost can no longer be ignored. Generally, machine parts are transported to and from machines by an automated material handling system. Material handling costs constitute a significant portion of a system's operating expense.

Replacement of a machine could very possibly change the machine assignment and hence the transportation design. In fact, the assignment of machined parts largely depends on two cost elements: (i) the cost of machining and (ii) the costs of transportation. Consider an example where an operation can be performed in either machine A and/or machine B with machining costs of $10 and $20 respectively; further suppose that the part is now at machine C with transportation costs of $30 from C to A and $10 from C to B. As one can observe, it is more economical for the part to travel to machine B despite its higher machining cost. This contrived exampled attempts to illustrate the trade-offs between machining cost and transportation costs, a consideration that should not be omitted for the FMS replacement environment.

V.2.3. Consideration on Material Handling Capacity

For an FMS replacement decision, the limitation of the material handling device could place a severe constraint on the assignment of machining parts thereby rendering certain replacement alternatives undesirable. For instance, the acquisition of more capacitated machines for the purpose of higher production levels implies that more workload will be placed upon the material handling device. If the workload exceeds the capacity of the transfer system, congestions and high in-process inventory are likely to occur. More importantly, finished parts could be waiting for the transfer device at the machine station, thus tying up the machine which could have been machining other parts. Or, machines are simply idle waiting for parts to arrive. Such phenomenon could translate into higher production costs which could imply that the acquisition of more capacitated machines is undesirable; or at the least, expansion of the material handling capacity is warranted. In short, FMS replacement decisions must explicitly account for the capacity of the material handling system.

V.2.4 Layout of New Machine

Since transportation can be a significant cost element, the issue of new machine layout requires attention in the evaluation of replacement alternatives. For a challenger can result in a superior overall performance while at one location, and inferior at another. This then raises the question of whether a completely new layout for the whole FMS should be configured, or whether the challengers should only be considered for locations currently occupied by the incumbents.

Ideally, a complete new layout configuration could be more economical; however, the fixed cost of such relocation could be significant. Also, there are physical constraints. Very likely, the locations where the machines can be installed is limited by such physical constraints as the hard wiring, floor space...,etc. Unless a significant number of machines are being replaced, there appears to be no apparent reason for a complete relayout of the facility. Further, while a new layout should be examined, the number of location alternatives are limited by the physical constraints.

V.2.5 Utilization of Inputs Among Machines

The cost of machining is directly related to the rate of input consumptions as well as the types of inputs required. Inputs commonly required for an CNC machining operation include energy, floor space, direct labor (skilled or unskilled), indirect labor, raw material, computer support...etc. In the case of single machine replacement, the tradeoff of input substitution brought about by different production technology is basically direct. Primarily, the comparison is between two machines which perform the same machining operations but consume different or different levels of inputs.

In an FMS replacement decision, such tradeoffs are much less obvious --particularly in cases where input resources are limited. For, in addition to the preceding situation, the analysis may be extended to situations where machining units perform different operations but consume a common input. Or, in another view, these machines are competing for the same resources. How the resources eventually get allocated will depend upon the demand placed upon the machines. The intent here is to identify the complexity involved regarding inputs substitutability. Further, the limited resources of certain inputs could render certain replacement alternatives infeasible. Take the case of skilled labor, if the supply of such input is limited, replacement alternatives which utilize large amounts of skilled labor could become infeasible.

V.3 REPLACEMENT POSSIBILITIES

The foregoing sections discussed the interacting nature of the FMS and how replacement alternatives are so affected. It was assessed that the selection of replacement machine will be affected by machining cost, transportation cost, workload mix, demand changes ... etc. The issue here is on the combinatorial nature of replacement possibilities.

Traditional replacement analysis primarily involves single machine replacements. That is, a single machine/system is replaced by another single machine/system. This one-for-one replacement situation is severely limited in application, particularly for an FMS. Machines in an FMS are not individual machines but are components of a single interrelated production system. More importantly, replacement of multiple machines are likely and replacement schemes which range from one-for-several to several-for-one are conceivable in the FMS environment. Naturally, there are constraints to these possibilities.

V.3.1 Complete and Partial Replacement

In an FMS, it is probable that the machines which are "ready" to be replaced are known in advance. Quite commonly, machines which were recently purchased would unlikely be considered as replacement candidates whereas ones that are considered as "old" would be likely candidates for replacement. In essence, in the context of replacement, there are two categories of machines: those which are candidates for replacement and those which are not. Naturally, the fact that these machines are candidates for replacement in no way implies that all of them will be replaced at the same time; or that all of them will be replaced during the planning period. It does, then, raise many possible replacement configurations. To facilitate this discussion, two new terms are introduced: (a) partial replacement -- situations where only a portion of the replacement candidates are replaced within the planning horizon and (b) complete replacement -- situations where all of the replacement candidates are replaced within the planning horizon. To see what these replacement siutuations are and how they could possibly generate multiple FMS configurations, consider the following example.

V.3.2 An Example

Let there be an FMS having four machines A, B, C, and D, with A and B as the replacement candidates. Further, assume that there are two challengers X and Y; and both are available over each of the next five years with each capable of replacing A or B, or both. Lastly, assume that both the challengers acquired will not be replacement candidates and that once a challenger is selected, it will be dropped from further consideration.

Table V.1 lists seven possible FMS configurations resulting from different replacement possibilities. For configurations one and two, machine B is replaced by challenger X in the former and by challenger Y in the latter. Likewise, machine A is replaced by challenger X in configuration three whereas in configuration four, it is replaced by challenger Y. For each of these four configurations, if no further replacement activities take place, and since there remains one replacement candidate, then these configurations (1-4) would represent partial replacement situations.

Configurations 5-7 represent complete replacements. In configuration five, both machine A and machine B are replaced by challenger X while in configuration six, the two defenders are replaced by challenger Y. To arrive at configuration seven, there could be several challenger-to-defender match-ups: (see Figure V.1).

(a) Challenger X first replaces defender B with challenger Y subsequently replacing defender A (path 0-1-7);

(b) Challenger Y first replaces defender B with challenger X subsequently replacing defender A (path 0-2-7);

(c) Challenger X first replaces defender A with challenger Y subsequently replacing defender B (path 0-3-7);

(d) Challenger Y first replaces defender A with challenger X subsequently replacing defender B (path 0-4-7);

(e) Concurrently, defenders A and B are replaced by challenger X and Y.

It is noted that the number of FMS configurations depends on both the number of defenders and the number of available challengers. The following section will discuss the combinatorial nature of these replacement possibilities.

Table V.1

Possible FMS Configurations

Configuration Number	Remaining Replacement Candidates	Challenger(s) Acquired	Other Machines on Hand
Status Quo	A,B	--	C,D
1	A	X	C,D
2	A	Y	C,D
3	B	X	C,D
4	B	Y	C,D
5	--	X	C,D
6	--	Y	C,D
7	--	X,Y	C,D

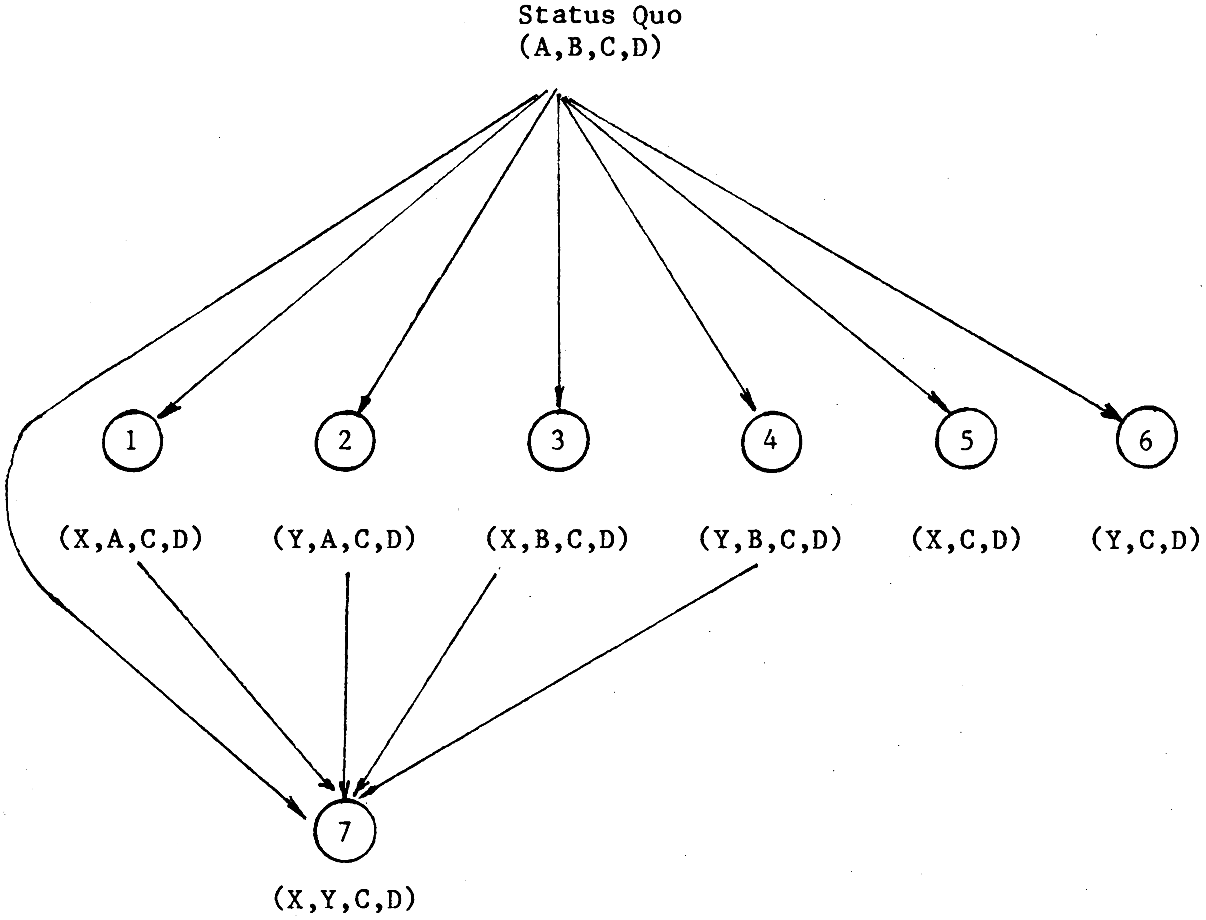


Figure V.1

Sequences of FMS Configuration

V.3.3 Possible FMS Configurations Resulting From Different Replacement Alternatives

The issue raised here is combinatorial in nature. To be general, assume that each of the challengers is capable of replacing each of the defenders as well as all of the defenders. Furthermore, assume that the number of machines in the FMS cannot exceed the number with which the system originally started. This assumption limits the size of the problem and is also valid in practice due to physical constraints. Finally, assume that the acquired challengers will not become replacement candidates and that once a challenger is acquired, it will not be considered further.

Let n be the total number of challengers available at each period
within the planning horizon,
d be the total number of defenders at present.

For $n \geq d$, the total number of possible FMS configurations is equal to the sum of all complete replacement configurations and all partial replacement configurations or

$$\sum_{i=1}^{d} C_i^n + \sum_{i}^{d-1} \sum_{j}^{d-i} (C_i^n)(C_j^d)$$

For $n < d$, the total number of possible FMS configurations is

$$\sum_{i=1}^{n} C_i^n + \sum_{i=1}^{n} \sum_{j=1}^{d-1} (C_i^n)(C_j^d)$$

To illustrate the size of these FMS configurations, let both n and d range from one to six. Table 4 shows different numbers of FMS configurations with respect to different (n,d) combinations. Note that the number of FMS configurations increases significantly as both n and d increase.

V.4 SUMMARY

This chapter outlined the major replacement considerations common to most FMS environment; unless these issues are addressed, an effective replacement policy is unlikely. It is also assessed that the FMS represents a complex multi-machine production environment and that single machine replacement models are inadequate. The next chapter attempts to formulate a replacement model appropriate for the FMS environment. Considerations discussed in this chapter will be incorporated along with other traditional replacement factors.

Table V.2

POSSIBLE FMS CONFIGURATIONS
FOR DIFFERENT (n,d) COMBINATIONS

	n =	1	2	3	4	5	6
	1	1	2	3	4	5	6
	2	3	7	12	18	25	33
	3	4	18	34	56	85	122
d =	4	15	41	83	147	240	370
	5	31	88	187	350	606	892
	6	63	183	402	794	1404	2445

CHAPTER VI

PRELIMINARY MODEL FORMULATION

VI.1. INTRODUCTION

Chapters II and III discussed the general nature of replacement problems. Several important factors were identified: (a) selection of replacement criterion, (b) selection of production technology, (c) selection of planning horizon, (d) input substitutions and (e) capacity expansion. In the preceding chapter, the FMS replacement environment is analyzed. It was pointed out that unless such issues as parts assignment, material handling cost, layout possibilities, replacement combinations, etc. are addressed, an effective replacement policy is unlikely. The framework is that machines within the FMS are interacting components and as such the interrelated effects caused by a new acquisition need to be evaluated.

In this chapter, a replacement model suitable for the FMS environment is formulated. This replacement model seeks to determine the sequence of FMS configurations which would maximize the production system's future worth. The maximization of profit will be used as the optimality criterion. The proposed model is demand driven. There are two parts to the formulation. The first part determines the optimal operating profit for a given FMS configuration at a given year. That is, based on both the price-volume relationship and operating costs structure, the annual optimal production levels for all parts are determined; at such production levels, the annual operating profit of the entire FMS is maximized. Here, if "pooling" is not allowed (i.e. when a part type is assigned to a particular machine for an operation for all identical parts), the problem is formulated as a series of zero-one linear programs. If "pooling" is allowed, the problem is formulated as a series of linear programs. The second part considers the optimal FMS configuration from period to period. A dynamic programming formulation is presented. That is, once the optimal operating profit per configuration per period is determined, the information is used to determine the optimal configuration sequence over the planning horizon. For equipment depreciation, the 1983 ACRS rules are used [ ].

It is noted that this problem approach focuses on the aggregate planning aspect of an FMS. Considerations of the operating characteristics are omitted. Namely, although this formulation obtains an overall balance of workload and capacity utilization, the issue of real time scheduling is not addressed. Also, considerations of such process planning issues as tooling setups, batching strategy, machine breakdown, in-process inventory, etc. are not considered. These are indeed relevant issues on the production floor. However, since replacement decisions are primarily investment decisions, an aggregate planning perspective is taken.

VI.2 DETERMINATION OF OPTIMAL OPERATING PROFIT WHEN POOLING IS NOT ALLOWED

In this section, the formulation for the determination of optimal operating profit is presented. This model is a series of linear zero-one mathematical programs. Assumptions will be discussed first, followed by the formulation of the objective function and then the constraint set.

VI.2.1 Assumptions

(i) The input/output coefficients are assumed to be linear. That is, the input requirements for the machines are assumed to have a proportionate relationship with the machine output. (ii) No pooling of parts assignment is allowed. When a part type is assigned to a particular machine for an operation, the same machine will perform the same operation for all identical parts. (iii) There will be no inventory carryover from year to year. (iv) The rates for the inputs to the machines are known. (v) The sequence of operations per part is predetermined. (vi) The material handling device is assumed to be an Automatic Guided Vehicle. (vii) Price-volume relationships are described by price breaks and parts produced will all be sold at the corresponding price.

VI.2.2 Modeling of the Objective Function

There are two primary cost elements: cost of transportation and cost of machining. The cost of transportation is directly related to the total distance travelled by all the parts. Let

$$X_{pkms} = \begin{cases} 1, & \text{if the } k^{th} \text{ operation of part } p \text{ is performed on the } m^{th} \text{ machine after visiting } s^{th} \text{ machine.} \\ 0, & \text{otherwise.} \end{cases}$$

d_{ms} = distance travelled from the s^{th} machine to the m^{th} machine, and

Q_p = the output level of part p, $p = 1, 2, \ldots, \tilde{p}$

The total distance travelled by all the parts machined is

$$\sum_p \sum_k \sum_m \sum_s \{X_{pkms} \quad d_{ms} \quad Q_p\} \qquad (1a)$$

where $k \in \{K_p\}$, i.e., k is the index of the element of the operation set required by part p.

$m \in \{M_{p,k}\}$, i.e., m is the index of the elements of the machine set which can perform operation k, and $s \in \{M_{p,k-1}\}$

Let α be the utilization rate of the AGV system and w be the cost per unit distance travelled. Then the total cost of transportation can be written as

$$\sum_p \sum_k \sum_m \sum_s \{X_{pkms} \quad d_{ms} \quad Q_p \quad w \frac{1}{\alpha}\} \qquad (1b)$$

Similarly, the total machining time required for the m^{th} machine can be expressed as

$$\sum_p \sum_k \{X_{pkms} \cdot T_{pkm}\} \qquad (2a)$$

where T_{pkm} is the processing time required by the k^{th} operation of part p on machine m.

Let the inputs per unit machine time to the m^{th} machine be U_{1m}, $U_{2m}, \ldots, U_{Sm}$ and $g_1, g_2, \ldots, g_\ell$ be the respective unit input costs. Then the cost per unit machine time for the m^{th} machine can be defined as

$$C_m = \sum_{\ell=1}^{\tilde{\ell}} g_\ell \, U_{\ell m} \tag{2b}$$

From equations (1b), (2a) and (2b), and letting P_pQ_p be the revenue contributed by part p, the objective function is written as

$$\underset{P_pQ_p \varepsilon \{(PQ)_p\}}{\text{MAX}} = \sum_p P_p \, Q_p - \sum_p \sum_k \sum_m \sum_s X_{pkms} \left[d_{ms} \, w \, \frac{1}{\alpha} + T_{pkm} \, C_m\right] Q_p \tag{3}$$

where $C_m = \sum_{\ell=1}^{\tilde{\ell}} g_\ell U_{\ell m} \quad \forall \; m = 1, 2, \ldots, M$

$\{(PQ)_p\}$ is the set of price-volume relationships for part p. (See Figure VI.1).

VI.2.3 Modeling of the Constraint Sets

There are two sets of constraints. The first set is of the logical nature. Here, constraints are developed to ensure that the assignment of parts meet routing feasibility, and to ensure that all the machining operations are uniquely performed. The second set is of an allocation nature. To ensure feasibility in allocation, upper limits are

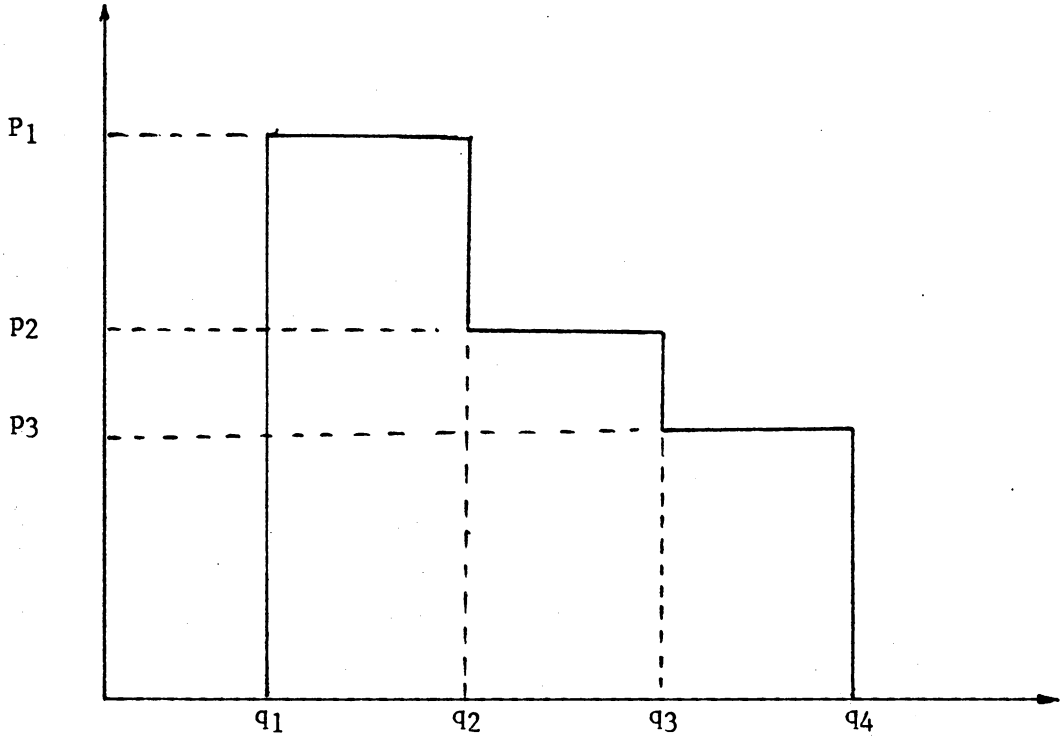


Figure VI.1

A Price-volume Relationship for a Given Part with Three Different Price Breaks.

established for various input quantitites, machine capacity as well as the material handling system capacity. Equations (4a-b) are logical constraints. Equations (5a-c) are allocation constraints. To guarantee that each operation per part is performed only once, the following constraints are needed

$$\sum_{m} \sum_{s} X_{pkms} = 1 \qquad \forall p = 1, 2, \ldots, \tilde{p} \qquad (4a)$$

In order for the routing of parts to be feasibly assigned, it is necessary that when the k^{th} operation is performed in machine $\hat{m}$, then the part p has to leave machine $\hat{m}$ in the $(k + 1)^{th}$ operation. That is,

$$\sum_{s} X_{pk\hat{m}s} = \sum_{m} X_{pk+1\hat{m}m} , \forall p = 1, 2, \ldots, \tilde{p} \qquad (4b)$$?

$$k \in \{k_p\}$$

$$\hat{m} \in \{M_{p,k}\}$$

where $s \in \{M_{p,k-1}\}$, and $m \in \{M_{p,k+1}\}$.

Let $\tilde{U}_{\ell}$ be the input amount available. Then for input type ℓ, the total amount consumed cannot exceed $\tilde{U}_{\ell}$. That is,

$$\sum_{p} \sum_{k} \sum_{m} \sum_{s} X_{pkms} \quad T_{pkm} \, Q_p \, U_{\ell m} \leq \tilde{U}_{\ell} , \forall 1 = 1, 2, \ldots, \tilde{\ell} \qquad (5a)$$

Likewise, let $\tilde{T}_m$ be the capacity of the m^{th} machine and $\tilde{D}$ be the capacity of the material handling system. The following constraints place upper limits on machine capacity and the material handling system capacity:

$$\sum_{p}\sum_{k}\sum_{s} X_{pkms} \quad T_{pkm} \; Q_p \leq \tilde{T}_m \qquad \forall \; m = 1, 2, \ldots, \tilde{m} \qquad (5b)$$

and

$$\sum_{p}\sum_{k}\sum_{m}\sum_{s} X_{pkms} \quad d_{ms} \frac{1}{\alpha} \; Q_p \leq \tilde{D} \qquad (5c)$$

VI.2.4 The Model to Maximize Operating Profit for Each Period per FMS Configuration When Pooling is Not Allowed

Combining the objective function and the constraint sets formulated in sections (2.2) and (2.3), the model is summarized as follows:

$$\underset{P_pQ_p \; \varepsilon\{(PQ)_p\}}{\text{MAX}} \quad \sum_{p} P_p \; Q_p - \sum_{p}\sum_{k}\sum_{m}\sum_{s} X_{pkms} \quad \{d_{ms} \; w \frac{1}{\alpha} + T_{pkm} \; C_m\}Q_p$$

where $C_m = \sum_{\ell} g_{\ell}U_{\ell m} \;\; \forall \; m = 1, 2, \ldots, \tilde{m}$, and

subject to

$$(1a) \quad \sum_{m}\sum_{s} X_{pkms} = 1, \quad \forall \; p = 1, 2, \ldots, \tilde{p}; \; k \; \varepsilon \; \{k_p\}$$

$$(1b) \quad \sum_{s} X_{pk\hat{m}s} = \sum_{m} X_{pk+1m\hat{m}} \qquad \forall \; p = 1, 2, \ldots, \tilde{p};$$

$$k \; \varepsilon \; \{k_p\}; \; \hat{m} \; \varepsilon \; \{M_{p,k}\}$$

$$(2) \quad \sum_{p}\sum_{k}\sum_{m}\sum_{s} X_{pkms} \quad T_{pkm} \; Q_p \; U_{\ell m} \leq U_{\ell} \quad \forall \; \ell = 1, 2, \ldots, \tilde{\ell}$$

$$(3) \quad \sum_{p}\sum_{k}\sum_{m}\sum_{s} X_{pkms} \quad T_{pkm}\, Q_p \leq \tilde{T}_m \qquad \forall\, m = 1, 2, \ldots, \tilde{m}$$

$$(4) \quad \sum_{p}\sum_{k}\sum_{m}\sum_{s} X_{pkms} \quad d_{sm} \quad Q_p \leq \tilde{D}$$

where $p = 1, 2, \ldots, \tilde{p}$; $k \,\varepsilon \{k_p\}$; $m \,\varepsilon \{M_{p,k}\}$; $m' \,\varepsilon \{M_{p,k-1}\}$ and all Xs are binary.

VI.3 DETERMINATION OF OPTIMAL OPERATING PROFIT WHEN POOLING IS ALLOWED

In this section, the formulation for the determination of optimal operating profit when pooling is allowed is presented. This model can be described as a multicommodity network-flow problem which can be formulated as a linear program [35]. Assumptions will be discussed first, followed by the formulation of the objective function and then the constraint set. Many assumptions and notational representations used in the preceding section also apply here.

VI.3.1 Assumptions

Except that pooling is now allowed, all other assumptions as stated in the preceding section remain applicable. From a workload balance standpoint, the allowance of pooling provides a better utilization of machine capacity. That is, not only can the workoload of a part type be divided among machines by operations (as is allowed in the preceding formulation) but the workload can now be further divided within the same operation.

VI.3.2 Modeling of the Objective Function

Define:

Y_{pkms} be the quantity of part "p" which flows from machine "s" to machine "m" for the k^{th} operation of the part.

The total cost of transportation for all part types is

$$\sum_p \sum_k \sum_m \sum_s \{Y_{pkms}\, d_{ms}\, \alpha\, w\} \qquad (6a)$$

The total cost of machining for all part types is

$$\sum_p \sum_k \sum_m \sum_s \{Y_{pkms}\, T_{pkm}\, C_m\} \qquad (6b)$$

The total revenue received for all part types is

$$\sum_p \sum_s \quad P_p\, Y_{p\tilde{k}\tilde{m}s} \qquad (6c)$$

where $\tilde{k}$ is the last opeation and

$\tilde{m}$ is the unloading area (last machine) where all parts travel to.

Also,

$$Q_p = \sum_s Y_{p\tilde{k}\tilde{m}s}, \text{ and}$$

$$P_pQ_p \;\varepsilon\; \{(PQ)_p\}$$

From equations (6a), (6b) and (6c), the objective function is written as

$$\underset{PpQp\ \varepsilon\{(PQ)p\}}{\text{MAX}} \quad \{\sum_p \sum_s P_p\, Y_{p\hat{k}\hat{m}s} - \sum_p \sum_k \sum_m \sum_s Y_{pkms}\, [d_{ms}\, \alpha\, w + T_{pkm}\, C_m]\} \quad (7)$$

where $C_m = \sum_{\ell=1}^{\tilde{\ell}} g_\ell U_{\ell m}$ and $Q_p = \sum Y_{p\tilde{k}\tilde{m}s}$

VI.3.3 Modeling of the Constraint Sets

As in the preceding section, there are two sets of constraints. The first set is of the logical nature, which ensures that the quantity of parts entering the machine is identical to the quantity that leaves. This assumes no scrap and loss during production. However, an extension to incorporate scrap/loss would be straight forward. The second set is of the allocation nature, which establishes upper limits on various inputs, on machine capacity as well as on the material handling system capacity. Equations (8) are logical constraints whereas equations (9a-c) are allocation constraints. They are:

(a) In-flows to a machine equals outflow -

$$\sum_{s} Y_{pk\hat{m}s} = \sum_{\hat{m}} Y_{pkm\hat{m}} , \quad \forall \; p = 1, 2, \ldots, \tilde{p} \qquad (8)$$

$$k \in \{K_p\}$$

$$s \in \{M_{p,k-1}\}$$

$$\hat{m} \in \{M_{p,k}\}$$

$$m \in \{M_{p,k+1}\}$$

(b) Upper limits on input amounts -

$$\sum_{p} \sum_{k} \sum_{m} \sum_{s} Y_{pkms} \, T_{pkm} \, U_{\ell m} \leq \tilde{U}_{\ell}, \quad \forall \; \ell = 1, 2, \ldots \tilde{\ell} \qquad (9a)$$

(c) Upper limits on machine capacities -

$$\sum_{p}\sum_{k}\sum_{s} Y_{pkms}\, T_{pkm} \leq \tilde{T}_{m}, \qquad \forall\, m = 1, 2, \ldots, \tilde{m} \qquad (9b)$$

(d) Upper limits on the AGV -

$$\sum_{p}\sum_{k}\sum_{m}\sum_{s} X_{pkms}\, d_{ms} \frac{1}{\alpha} \leq \tilde{D}$$

VI.34 The Model to Maximize Operating Profit for Each Year per FMS Configuration When Pooling is Allowed

Combining the objective function and the constraint sets formulated in sections (3.2) and (3.3), the entire model is written as follows:

$$\underset{P_pQ_p\ \varepsilon\{(PQ)_p\}}{\text{MAX}} \quad \{\sum_{p}\sum_{s} P_p\, Y_{p\tilde{k}\tilde{m}s} - \sum_{p}\sum_{k}\sum_{m}\sum_{s} Y_{pkms}\, [d_{ms}\, \alpha\, w + T_{pkm}C_{m}]\}$$

such that

$$\sum_{s} Y_{pk\hat{m}s} = \sum_{\hat{m}} Y_{pkm\hat{m}}\ ; \qquad \forall\ p = 1, 2, \ldots, \tilde{p}$$

$$k\ \varepsilon\ \{K_p\}$$

$$S\ \varepsilon\ \{M_{p,k-1}\}$$

$$\hat{m}\ \varepsilon\ \{M_{p,k}\}$$

$$m\ \varepsilon\ \{M_{p,k+1}\}$$

$$\sum_p \sum_k \sum_m \sum_s Y_{pkms} \, T_{pkm} \, U_{\ell m} \le \tilde{U}_\ell \, ; \qquad \forall \; \ell = 1, 2, \ldots, \tilde{\ell}$$

$$\sum_p \sum_k \sum_s Y_{pkms} \, T_{pkm} \le \tilde{T}_m ; \qquad \forall \; m = 1, 2, \ldots, \tilde{m}$$

$$\sum_p \sum_k \sum_m \sum_s Y_{pkms} \, d_{ms} \frac{1}{\alpha} \le \tilde{D}$$

$$C_m = \sum_{\ell=1}^{\hat{\ell}} g_\ell U_{\ell m} \qquad Q_p = \sum_s Y_{pk\tilde{m}\tilde{s}}, \text{ and all Ys} \ge 0.$$

VI.4 DETERMINATION OF OPTIMAL CONFIGURATION SEQUENCE

In this section, the formulation for the determination of an optimal FMS configuration sequence is presented. Assumptions and definitions are provided first, followed by a formulation.

VI.4.1. Assumptions

(i) The total number of machines in the FMS cannot exceed the original number of machines in the system. (ii) Once a challenger is introduced into the FMS, it will not be considered further as a challenger. (iii) When a new machine is acquired, it will not become a replacement candidate. (iv) All machines to be replaced are known and are ready to be replaced at the beginning of the planning horizon. (v) The sale of the incumbent machine takes place at the beginning of the year, this assumption allows capital recovery of the preceding year to be claimed in full. Machine market values are assumed to be equal to the book value; the 1983 ACRS depreciation schedule is used. Investment tax credit will not be incorporated.

VI.4.2 Definitions of Terms

(i,j,t)	A triple denoting the i^{th} FMS configuration of j^{th} vintage type, operating in year t.
OP_{ijt}	Maximum operating profit of the FMS, in year t characterized by (i,j,t).
W_{ijt}	Machine value at year t for configuration (i,j,t).
D_{ijt}	Depreciation charge at year t for configuration (i,j,t).
r	Time value of money.
ρ	Income tax rate
T	The planning horizon.

VI.4.3 Forward Recursive Dynamic Programming Formulation

The determination of optimal FMS sequence can be viewed as a multistage problem with sequential decisions. Figure VI.2 illustrates this sequential structure. The output of each decision stage is the FMS configuration which then becomes the input to the next decision stage. The decision at each stage are the selection of challengers and

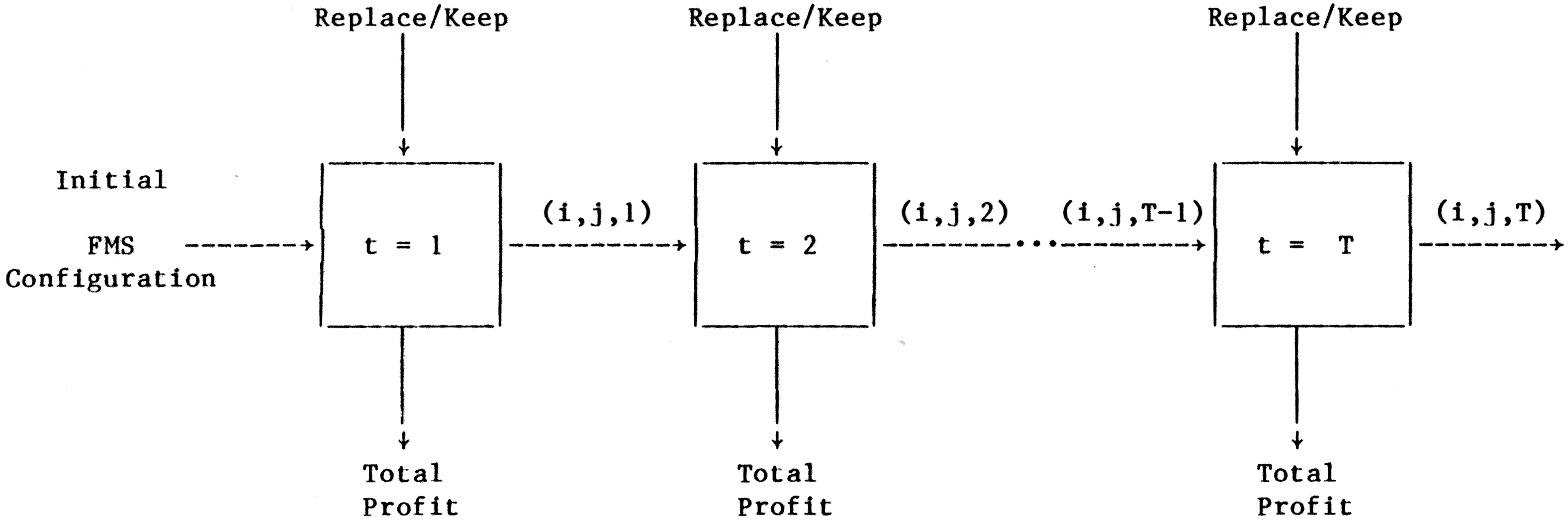


Figure VI.2

FMS Configurations Selection in a
Multistage Sequenctial Decision Framework

defenders as well as the parts assignment. The stage return is the operating profit of the FMS.

Let the optimal value function f_{ijt} be the optimal future worth for the FMS (of i^{th} configuration, j^{th} vintage type, operating in year t) from year one to year T if optimal replacement strategy is pursued during this time horizon.

As the first stage (t = 1), the optimal value function can be expressed as

$$f_{i11} = \{-W_{i11}\,(1+r) + (1-\rho)(OP_{i11}-D_{i11}) + W_{i12}\}(1+r)^{T-1},$$

and since $D_{i11} = W_{i11} - W_{i12}$, then

$$f_{i11} = \{-W_{i11}\,r + (1-\rho)(OP_{i11} - D_{i11})\}(1+r)^{T-1},\ \forall\ i \in \{I_1\} \quad (5)$$

where I_1 is the set of possible FMS configuration at this stage.

The explanation of Equation (5) is as follows: at year one, if FMS configuration (i,1,1) is required, then this involves the initial purchase value of new challengers for this configuration. Once purchased, the optimal value is obtained by achieving the optimal operating profit. The capitalized cost at this year consists of (a) the opportunity cost, $W_{i11}(r)$, (b) machine depreciation, D_{i11}. The tax outflow is $\rho(OP_{i11} - D_{i11})$.

From stage 2 to stage T, the recursive relationship can be established as follows:

If $j \varepsilon \{J_{1,t}\}$, where $\{J_{1,t}\}$ is the set of FMS configuration which does not consist of any new addition in this year, then

$$f_{ijt} = f_{ijt-1} + \{-W_{ijt}(r) + (1-\rho)(OP_{ijt} - D_{ijt})\}(1+r)^{T-t}$$

$$\begin{array}{ll} V \;\; i \,\varepsilon\, \{I_t\} & \\ j \,\varepsilon\, \{J_{1,t}\} & (6a) \\ t = 2,3,\ldots,T & \end{array}$$

Equation (6a) states that if there are no replacements in year t (as implied by the condition $j \varepsilon \{J_{1,t}\}$), then the best f_{ijt} up to this point is simply the f_{ijt-1} from the preceding year plus the current year's optimal operating profit, minus depreciation, opportunity cost and tax for year t.

If $\hat{j} \varepsilon \{J_{2,t}\}$, where $\{J_{2,t}\}$ is the set of FMS configurations which consists of new additions in this year, then

$$f_{\hat{i}\hat{j}\hat{t}} = \{-W_{\hat{i}\hat{j}\hat{t}}(r) + (1-\rho)(OP_{\hat{i}\hat{j}\hat{t}} - D_{\hat{i}\hat{j}\hat{t}})\}(1+r)^{T-\hat{t}}$$

$$\begin{array}{lll} \forall\; \hat{i} \,\varepsilon\, \{I_t\} & & \\ \hat{j} \,\varepsilon\, \{J_{2,t}\} \quad + \text{MAX} & \left\{ \begin{array}{ll} f_{ij\hat{t}-1}; & \forall\; i \,\varepsilon\, \{I_{i,j,t-1}\} \\ & j \,\varepsilon\, \{J_{i,t-1};\, J_{2,t-1}\} \\ & j \,\varepsilon\, \{J_{i,tiJ2,t}\} \end{array} \right. & (6b) \\ \hat{t} = 2,3,\ldots,T & & \end{array}$$

I_{ijt-1} is the set of possible FMS configurations in year t-1 which can be changed to the current configuration $(\hat{i},\hat{j},\hat{t})$.

Here, when the current FMS configuration indicates new equipment addition, then the optimal function f_{ijt} can be represented by the optimal operating profit minus opportunity cost, depreciation, and tax plus the maximum f-value of any possible configuration (in year t-1) which can change to the current configuration. When the optimal $F_{i,j,T}$ is determined, the sequential decisions leading to this result can then be traced back by examining equations (5,6a-b). These decisions at each stage represent the optimal replacement policy. A backward recursive dynamic programming formulation is also provided in Appendix II.

VI.5 SCOPE OF THIS RESEARCH

A replacement model for an FMS has been formulated. It is apparent that this is a very large problem. Before assessing the size of this problem, it is necessary to determine whether the assumption of pooling should be explored. As discussed earlier, pooling allows a better balance of workload ahd hence a more efficient utilization of machines can result. However, the implementation of such a scheme could indeed be quite difficult. In order to be consistent with the aggregate planning approach of this research, it is assessed that the pooling assumption should be adopted from hereon. As such, the size of this problem is depicted as follows:

(i) Determination of the maximum operating profit with pooling - The maximum number of decision variables per price-volume relation per configuration is

$$= \tilde{p}\ \tilde{k}\ \tilde{m}\ \tilde{m}.$$

And the corresponding maximum number of constraints is

$$= \tilde{p}k + \tilde{p}\tilde{k}\tilde{m} + \tilde{\ell} + 1$$

If the number of price breaks is $\tilde{\mu}$, this means the above problem needs to be solved $\tilde{\mu}$ times.

(ii) Optimal FMS sequence

The number of stages is T.

The maximum number of f_{ijt} is

$$= \hat{i} \sum_{t=1}^{\hat{t}} t.$$

VI.6 Summary

This chapter provided on economic replacement model formulation for an FMS environment. All the relevant issues discussed in the preceeding chapter are incorporated. There are two parts to the formulation; the first determines the maximum operating profit per FMS configuration per year. The second part uses the results of the first part to construct an optimal FMS configuration sequence which in turn results in both an optimal replacement policy and an expansion/contraction policy. In fact, one may view the first part as a sub-problem of the second.

In the next chapter, an illustrative example for the assignment of machine parts for different FMS configurations are examined. This illustration sets the perspective for the multi-period model to follow.

CHAPTER VII

ASSIGNMENT OF MACHINING PARTS WITHOUT REPLACEMENT - SINGLE YEAR MODEL

VII.1 INTRODUCTION

This chapter discusses the determination of the optimal operating profit for a given FMS configuration. This determination requires information on price-volume relationships, input rates to machines, unit costs, machine rates by operation per part types, layout of the FMS, availability of inputs, capacities of machines, and the capacity of the AGV system and its cost per unit distance travel. An illustrative problem is provided along with a solution procedure based on linear programming. The optimal machine parts assignment and its corresponding price-volume relationship are determined. Discussions on various aspects are included.

VII.2 PROBLEM STRUCTURE

VII.2.1 Problem Structure

The problem, as defined in Section VI.3, essentially consists of solving a problem with the following structure:

$$\begin{array}{llll} \text{MAX} & \text{MAX } P^{(1)}Y - CY; & \text{MAX } P^{(2)}Y - CY; \cdots; & \text{MAX } P^{(n)}Y - CY \\ & A_1Y = 0 & A_1Y = 0 & A_1Y = 0 \\ & A_2Y \leq b & A_2Y \leq b & A_2Y \leq b \end{array}$$

$$q^{(1)} \leq Y \leq q^{(2)} \qquad q^{(2)} + 1 \leq Y \leq q^{(3)} \qquad q^{(n)} + 1 \leq Y \leq q^{(n+1)}$$

$$0 \leq Y \leq q^{(2)} \qquad 0 \leq Y \leq q^{(3)} \qquad 0 \leq Y \leq q^{(n+1)}$$

where A_1 is the matrix for the flow of parts through the machine stations. Matrix A_1 has a diagonal block structure with each block representing material flow of a part type.

A_2 is the matrix for the consumption of resources and all elements of A_2 are positive.

b is the upper limit of resource consumptions.

$p^{(i)}$ $i=1,\dots,n$ is the price vector for the i^{th} price combination, $q^{(i)} + 1$, $q^{(i+1)}$ are the corresponding lower and upper limit vectors for the output level $\hat{Y}$, and

C is the vector of cost coefficients.

The above formulation requires solving a series of multi-commodity network flow problems. To illustrate this problem further, a simple case is depicted in Figure VII.1.

Here, ABCD is the feasible region bounded by the A_1Y and A_2Y constraints set. Region 1 is the feasible region bounded by the first price-break of both Y_1 and Y_2; similarly, region 2 by the first and the second, region 3 by the second of both, and region 4 by the second and the first. Since the price vectors are different for each price-break combination, the objective coefficients vary for each of these four regions. Therefore, the determination of the maximum operating profit for the entire combination set requires solving each of the combinations which as a linear programming structure with upper and lower bounding on the variables.

VII.2.2 On Infeasibility

For the preceding problem, certain infeasibility situations could occur which can eliminate the feasibility of certain price-break combinations. Consider the situation depicted in Figure VII.2. The first step involves the determination of the maximum operating profit for region 1 (feasible solution exists). Suppose that the process is pursued onto region 2, and no feasible solution can result for this region. This implies that region 3 and 5 cannot provide a feasible solution since the output requirements for both region 3 and 5 dominates that of region 2. Similarly, regions 6, 7, 8 can also be eliminated. However, nothing can be said about region 4 at this point. The reason is that, although at this region the output level of Y_2 is greater than that of Y_2 in region 2, the output level of Y_1 is lower. And this allows the trade-offs for the consumption of resources by the two part types. Should region 4 also produce an infeasible solution such as depicted in the figure, then region 9 is also infeasible.

In general, when a given price combination is found infeasible, then any price combination whose output requirement dominates this

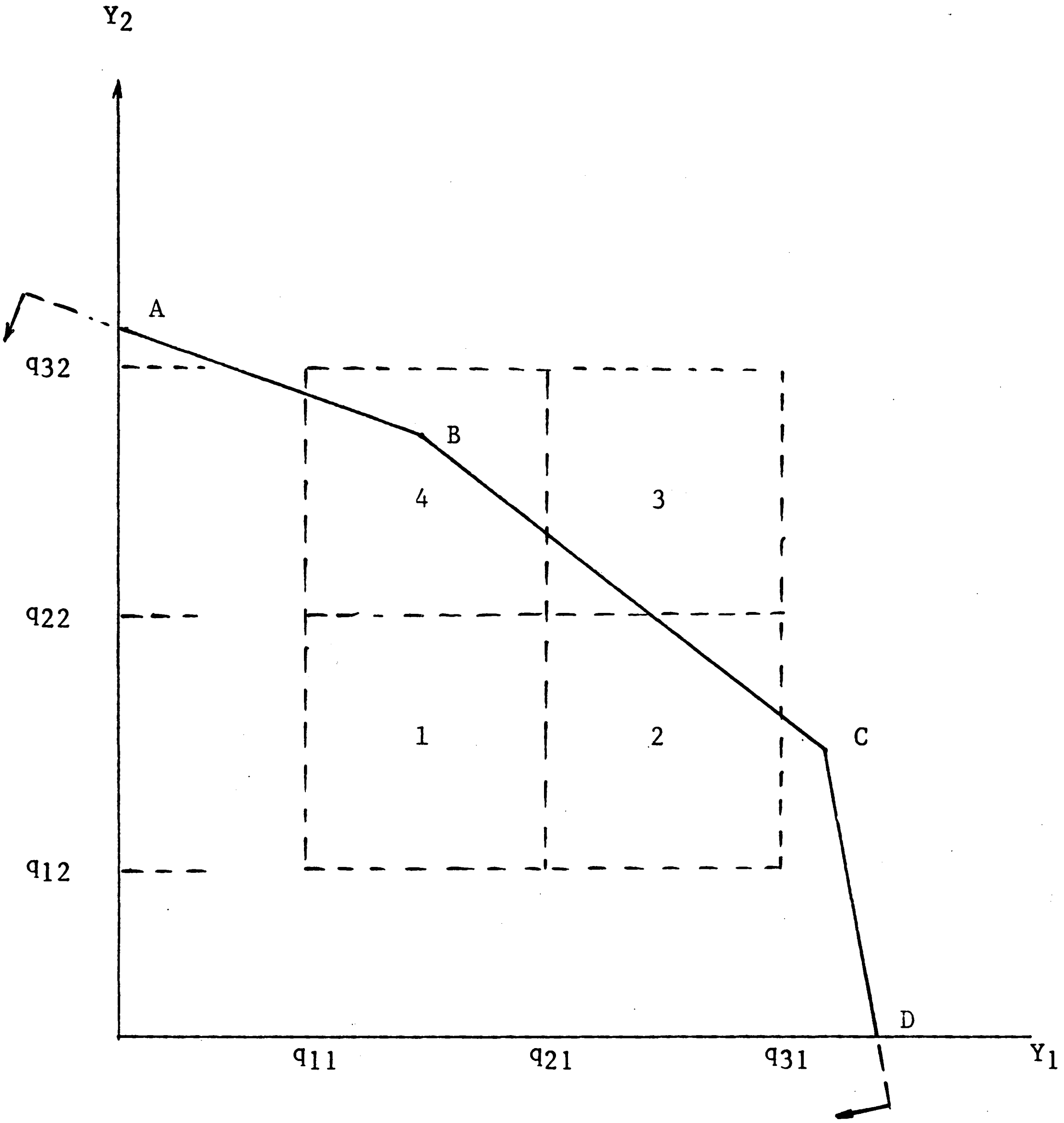


Figure VII.1

A Representation of the Flow Problem

infeasible price combination can be eliminated from further consideration. Hence, in order to systematically determine the maximum operating profit, the lowest price-break vector is tried first and when infeasibility is encountered, the elimination procedure is performed. In this manner, the soltuion to this problem can be obtained by systematically solving a series of linear programs.

VII.2.3 On the Size of the Decision Variable Set

The decision variables for each of the series of linear programs are the Y_{pkms}, and the maximum number of variables each L.P. can have is (p)(k)(m)(s). But since there will be operations of certain part types which cannot be machined by a particular machining station, then many of these variables can be eliminated. What is suggested here is that before the linear program is setup, the Y_{pkms} variables are first transformed into a single variable set with all the unnecessary s variables eliminated.

VII.2.4 The Linear Programming Subroutine

The linear programming subroutine used for the determination of operating profit is contained in Appendix VI [36]. This subroutine uses the revised simplex method and implicitly carries the upper bounding constraints. The two-phase method is used to obtain the initial basic feasible solution.

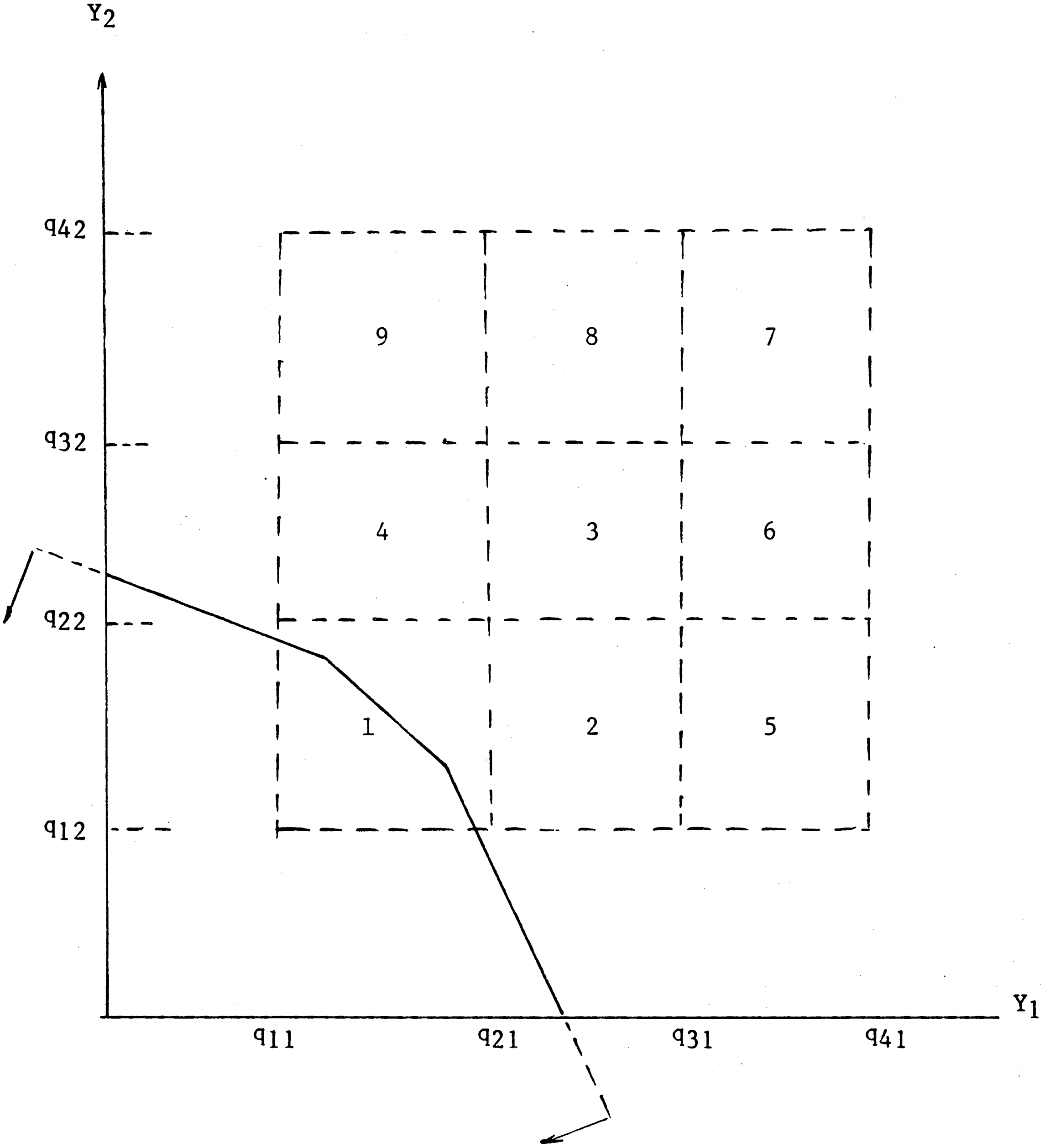


Figure VII.2

A Representation of the Flow Problem
Showing Infeasible Price Combinations

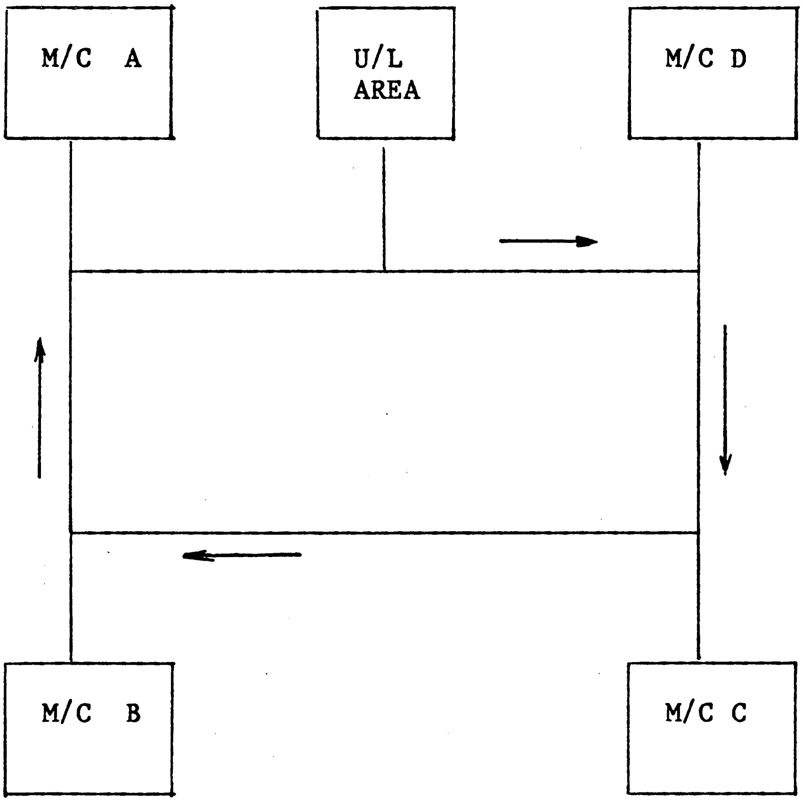
VII.3 AN ILLUSTRATIVE EXAMPLE

VII.3.1 An Illustrative Example

Consider an FMS with four machines and a single load-and-unload station. The layout for this FMS is shown in Figure VII.3 The distance between machines (distance matrix) is shown in Table VII.1. There are four major inputs to each of the four machines, namely: (a) direct labor, (b) indirect labor, (c) energy, and (d) maintenance. The respective consumption rate (input amount per machine-minute) and the unit cost of respective inputs are listed in Table VII.2. This FMS manufactures three parts. The machining times for each operation per part type for each machine are listed in Table VII.3. The resources available for each of the four inputs, the machine capacities of A, B, C and D, the capacity limit of the AGV and its cost per unit distance traveled are listed in Table VII.4. The price-volume relationships of the three part types are shown in Figure VII.4. All assumptions follow that of Section VI.3 and the objective is to determine both the price-volume combination of each of three part types and the corresponding machine parts assignment which would result in the maximum operating profit. The next section discusses the solution procedure.

VII.3.2 The Problem Size and Its Setup

There are three price-breaks for each part type. This means that there exists (3 x 3 x 3) = 27 price-break combinations and hence 27 price vectors, i.e, $p^{(i)}$, i = 1, ..., 27. The maximum number of



→ Direction of travel for AGV

Figure VII.3

The FMS Layout

Table VII.1

The Distance Matrix for the Example FMS

	L/U AREA	M/C A	M/C B	M/C C	M/C D
L/U AREA	0	80	60	40	20
M/C A	20	0	100	60	40
M/C B	40	20	0	80	60
M/C C	80	60	40	0	100
M/C D	100	80	60	20	0

variables for this problem is (6 + 7 + 10)(5)(5) = 575 where 6, 7, 10 are the total number of operations for part types one, two, and three, respectively. The total number of stations is five, four of which are machine stations and one load-and-unload station. Many of these Y_{pkms} variables have zero values since certain operations cannot be performed on certain machines; thus, they can be eliminated. For example, the variable $Y_{12BA} = 0$ since machine B cannot perform the 2nd operation of part one. Similarly, variable $Y_{12CD} = 0$, for although operation two of part type one can be performed on machine C, this part cannot come from machine D which cannot perform this part's first operation.

Using the preceding logic, all the Y_{pkms} are redefined using a single subscript (a single array in the FORTRAN program). The new variable set, its representation and objective coefficients are listed in Table VII.5. Note that the objective coefficients are all reversed in sign due to the built-in minimization structure of the linear program subroutine. There are 82 variables. The number of constraints in this problem is the sum of the total number of balance equations for the material flow and the total number of resource allocation constraints. There are 43 balance equations. This could be computed by summing the number of T_{pkm} which has a value greater than or equal to zero. In the terminology of network flow, there exists 43 nodes through which the commodities can flow. Since there are four inputs to the FMS, four machines, and an AGV systems, there are 9 allocation constraints. All together, there are 52 constraints.

Table VII.2

Respective Input Consumption Rates by Machine and Unit Costs of Inputs

	Direct Labor (min)	Indirect Labor (min)	Energy 75 kw m/c (kw hr)	Maintenance (min)
M/C A	.5	.3	.6	.1
M/C B	.6	1.0	.8	.2
M/C C	.55	.7	.7	.15
M/C D	.65	.4	.65	.1
Unit Cost of Respective Inputs:	$25/hr ($.4167 per min)	$35/hr ($.5833 per min)	$15/hr ($.25 per min) @ .20/ kw/hr	$15/hr ($.25 per min)

Table VII.3

Machine Times per Operation Per Part Type per Machine (in Minutes)

Part One:

Operation No.	M/C No.	1 L/U	2 A	3 B	4 C	5 D
1		*	18.5	14.5	*	*
2		*	*	*	10.0	*
3		*	*	10.5	8	12.5
4		*	23.5	*	*	25
5		*	*	*	15	16.5
6		0	*	*	*	*

Part Two:

Operation No.	M/C No.	1 L/U	2 A	3 B	4 C	5 D
1		*	*	47.9	*	*
2		*	33.2	40.0	*	*
3		*	15.0	20.0	*	*
4		*	*	*	40.0	36.8
5		*	*	*	35.0	38.4
6		*	14.5	*	*	15.0
7		0	*	*	*	*

Part Three:

Operation No.	M/C No.	1 L/U	2 A	3 B	4 C	5 D
1		*	36.3	34.5	*	*
2		*	32.0	*	40.0	34.8
3		*	*	*	15.0	*
4		*	10.0	10.0	*	*
5		*	*	30.6	*	25.0
6		*	*	*	10.0	9.4
7		*	20.0	20.0	*	*
8		*	18.0	*	17.0	*
9		*	5.8	5.0	*	*
10		0	*	*	*	*

* - not able to perform.

Table VII.4

Upper Limits of Resources

INPUTS AVAILABILITY:

Direct Labor - 1,200,000 hrs.

Indirect Labor - 1,200,000 hrs.

Energy - 10,000,000 kw hr.

Maintenance - 600,000 hrs.

MACHINE CAPACITY:

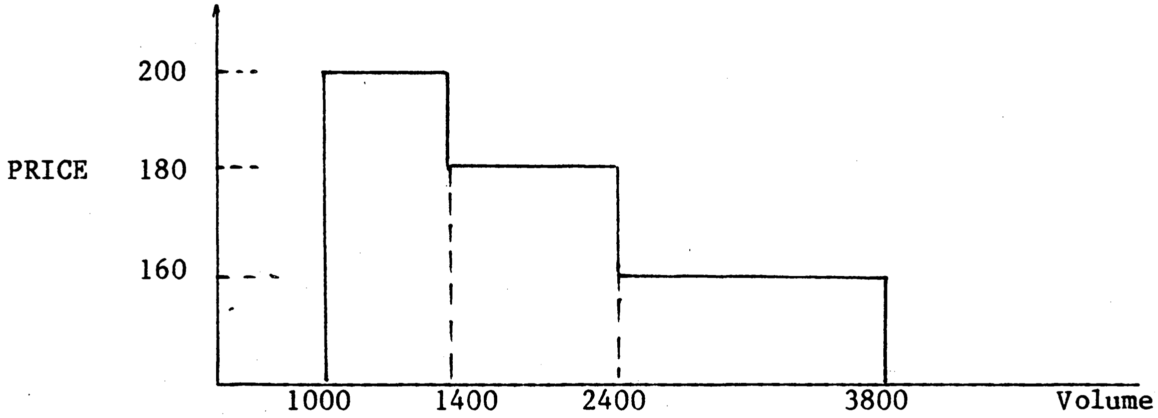
Machine A = 480,000 hrs.
Machine B = 480,000 hrs.
Machine C = 480,000 hrs.
Machine D = 480,000 hrs.

CAPACITY OF THE MATERIALS HANDLING SYSTEM:

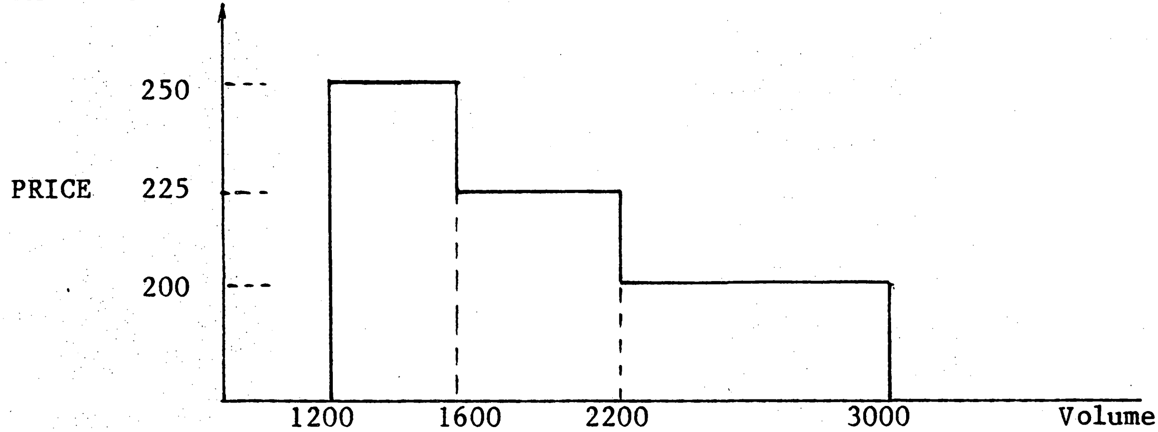
AGV (capacity) = 72,000,000 ft.

Cost per foot traveled by AGV = $0.1

PART ONE



PART TWO:



PART THREE:

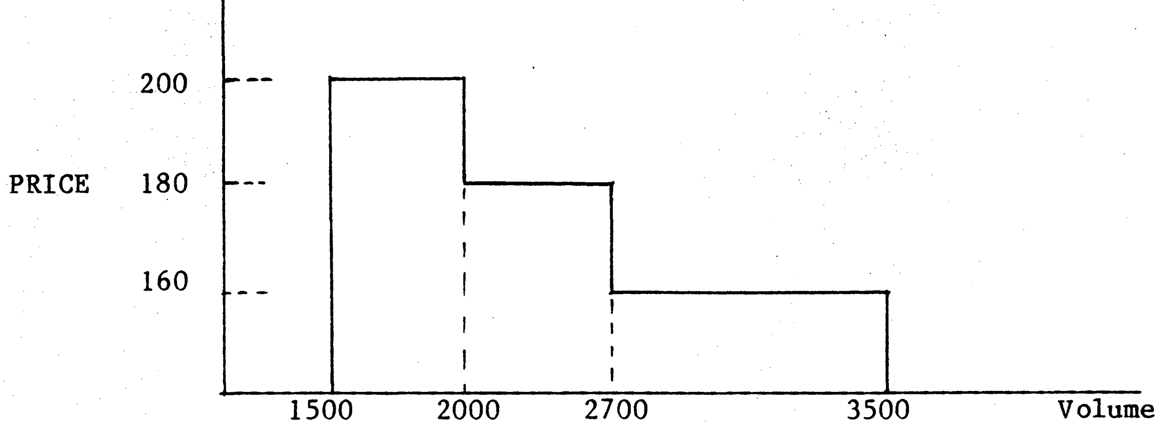


Figure VII.4

Price-Volume Relationship

However, there are upper and lower bounding for the decision variables. For example, if the price-break combination is {(1,2); (2,1); (3,3)}, i.e. the 2nd price break of part type one, 1st price-break of part type two and 3rd price-break of part type three, then the variables corresponding to the 1st, 2nd and 3rd part type would have an upper bound of 2400, 600, and 3500, respectively. For the variables that correspond to the flow of parts into the load-and-unload station, in addition to the corresponding upper bounds, lower bounds of 1400, 1200, and 2700 will need to be imposed. As previously mentioned, the linear programming subroutine used for the work has special treatment for such upper and lower bounding structure; all the bounds are carried implicitly through each pivot.

Lastly, the $[A_1 + A_2]$ matrix is setup accordingly. The task then is to determine the maximum operating profit for each price-break combination and to select the maximum from the whole combination set. The next section discusses the results for this problem.

VII.3.3 Results and Discussion

The optimal machine parts assignment for this problem is shown in Table VII.5. The price-break combinations are \$160, \$250, and \$350 respectively for parts one, two and three. The routes of the three part types are as follows: (See also Figure VII.7 which summarizes this and other results at the end of this chapter).

Table VII.5

Parts Assignment for the Example Problem

The Optimum is 897094.812

```
THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

       P     K     M     S      OBJ.       Y(P,K,M,S)
                                COEFF.

  1    1     1     2     1      20.94      3799.99
  2    1     1     3     1      23.71         0.0
  3    1     2     4     2      16.50      3799.99
  4    1     2     4     3      19.17        -0.00
  5    1     3     3     4      16.71         0.0
  6    1     3     4     4       6.80      3799.99
  7    1     3     5     4      21.98         0.0
  8    1     4     2     3      15.79         0.00
  9    1     4     2     4      21.12       140.00
 10    1     4     2     5      23.79         0.0
 11    1     4     5     3      25.29         0.0
 12    1     4     5     4      30.62      3659.99
 13    1     4     5     5      17.29         0.00
 14    1     5     4     2      20.75         0.00
 15    1     5     4     5      15.42         0.0
 16    1     5     5     2      16.75       140.00
 17    1     5     5     5      11.41      3659.99
 18    1     6     1     4      10.67         0.0
 19    1     6     1     5      13.33      3800.00
 20    1     6     1     1    -160.00      3800.00
 21    2     1     3     1      59.89      1600.00
 22    2     2     2     3      21.20      1600.00
 23    2     2     3     3      43.33         0.0
 24    2     3     2     2       8.38      1600.00
 25    2     3     2     3      11.04         0.00
 26    2     3     3     2      35.00         0.0
 27    2     3     3     3      21.67        -0.00
 28    2     3     4     2      20.75         0.0
 29    2     3     4     3      23.42         0.0
 30    2     4     4     2      42.00         0.00
 31    2     4     4     3      44.67         0.0
 32    2     4     4     4      34.00         0.00
 33    2     4     5     2      30.79      1600.00
 34    2     4     5     3      33.45        -0.00
 35    2     4     5     4      38.79         0.0
 36    2     5     4     4      29.75         0.00
 37    2     5     4     5      32.42         0.0
 38    2     5     5     4      39.89         0.0
 39    2     5     5     5      26.56      1599.99

 40    2     6     2     4      16.10         0.0
 41    2     6     2     5      18.76         0.00
 42    2     6     5     4      23.71         0.0
 43    2     6     5     5      10.37      1599.99
 44    2     7     1     2       2.67         0.0
 45    2     7     1     5      13.33      1599.99
 46    2     7     1     1    -250.00      1600.00
 47    3     1     2     1      30.93      2699.99
 48    3     1     3     1      45.37         0.00
 49    3     2     2     2      17.87      2699.99
 50    3     2     2     3      20.53         0.0
 51    3     2     4     2      42.00         0.0
 52    3     2     4     3      44.67         0.0
 53    3     2     5     2      29.40         0.0
 54    3     2     5     3      32.07         0.0
 55    3     3     4     2      20.75      2699.99
 56    3     3     4     4      12.75         0.00
 57    3     3     4     5      15.42         0.00
 58    3     4     2     4      13.58      2700.00
 59    3     4     3     4      16.17        -0.00
 60    3     5     3     2      46.48         0.0
 61    3     5     3     3      33.15         0.00
 62    3     5     5     2      22.62      2700.00
 63    3     5     5     3      25.29        -0.00
 64    3     6     4     3      19.17         0.0
 65    3     6     4     5      11.17         0.00
 66    3     6     5     3      14.50         0.0
 67    3     6     5     5       6.50      2699.99
 68    3     7     2     4      19.17         0.0
 69    3     7     2     5      21.83      2699.99
 70    3     7     3     4      27.00         0.0
 71    3     7     3     5      29.67         0.0
 72    3     8     2     2      10.05      2699.99
 73    3     8     2     3      12.72         0.00
 74    3     8     4     2      22.45         0.0
 75    3     8     4     3      25.12         0.0
 76    3     9     2     2       3.24      2699.99
 77    3     9     2     4      11.24         0.00
 78    3     9     3     2      18.75         0.0
 79    3     9     3     4      10.75         0.0
 80    3    10     1     2       2.67      2699.99
 81    3    10     1     3       5.33         0.00
 82    3    10     1     1    -350.00      2700.00
```

Part One: Operation 1 - 3800 units from load/unload (L/UL) station (station 1) to machine 2.
Operation 2 - 3800 units from machine 2 to machine 4.
Operation 3 - 3800 units from machine 4 to itself.
Operation 4 - 140 units from machine 4 to machine 2 and 3660 from machine 4 to machine 5.
Operation 5 - 140 units from machine 2 to machine 5 and 3660 units from machine 5 to itself.
Operation 6 - 3800 units from machine 5 to station 1.

Part Two: Operation 1 - 1600 units from the U/L station to machine 3.
Operation 2 - 1600 units from machine 3 to machine 2.
Operation 3 - 1600 units from machine 2 to itself.
Operation 4 - 1600 units from machine 2 to machine 5.
Operation 5 - 1600 units from machine 5 to itself.
Operation 6 - 1600 units from machine 5 to itself.
Operation 7 - 1600 units from machine 5 to L/UL station.

Part Three: Operation 1 - 2700 units from L/UL station to machine 2.
Operation 2 - 2700 units from machine 2 to machine 2.
Operation 3 - 2700 units from machine 2 to machine 4.
Operation 4 - 2700 units from machine 4 to machine 2.
Operation 5 - 2700 units from machine 2 to machine 5.
Operation 6 - 2700 units from machine 5 to machine 5.

Operation 7 - 2700 units from machine 5 to machine 2.
Operation 8 - 2700 units from machine 2 to itself.
Operation 9 - 2700 units from machine 2 to itself.
Operation 10 - 2700 units from machine 2 to machine 1.

The breakdown of costs and revenue is shown in Table VII.6. Part type 3 gave the highest unit profit margin as well as the highest percentages of profit contribution, followed by part type 2 and part type 1. From the distribution of work load, one could observe that machine A (station 2) picked up most of the workload. In fact, from the optimal dual variables (Table VII.7), one could deduce that the utilization of machine A is at its upper limit. Another evidence of this is also exhibited in operation 4 of part type 1 where, instead of routing all machining parts to machine A, 3660 units were routed to machine D which has a higher operating cost for that operation.

The fact that output levels of each part type are at their upper limits can be explained by one or more of the following reasons:

(a) The total profit at this price range is the highest possible. Consider Figure VII 5a. If the total profit obtained by producing at the upper limit of the 1st price break is greater than that of the 2nd and third, i.e. $(P_X q_X - Cq_X) < (P_Y q_Y - Cq_Y) < (P_Z q_Z - Cq_Z)$, then there is no incentive to operate at a higher level.

(b) The total profit at the next level is prohibited by the capacity constraint(s). Consider Figure VII 5b. Although the

Table VII.6

Breakdown of Costs and Revenues by Part Type

	Part Type 1	Part Type 2	Part Type 3	Total
Output Level	3800	1600	2700	8300
Total Cost	377898	272832	405108	1055838
Unit Cost	99.45	170.52	150.04	127.209
Total Revenue	608000	400000	945000	1953000
Selling Price	160	250	350	235.3
Unit Profit	60.55	79.48	199.96	108.09
Total Profit	230090	127168	539892	897150
%Profit Contribution by Part Type	25.65%	14.17%	60.18%	100%

total profit obtained from producing at the upper limit of the 2^{nd} price break may be found to be greater than that of the 1^{st}, i.e, $P_X q_X - Cq_X < P_Y q_Y - Cq_Y$, this production level can in fact violate certain capacity constraint(s). And where the resource constraints allow, say up to q_y' the total profit may not be as attractive as producing at q_X, i.e. $P_X q_X - Cq_X < P_Y' q_Y' - Cq_y'$,.

(c) The total profit at the next level is diminished by the higher unit operating cost. This could also occur to both (a) and (b). Consider Figure VII 5c. If the total profit from producing at q_X is greater than that of q_Y, i.e. $P_X q_X - C_X q_X < P_y q_y - C_Y q_Y$, where $C_Y < C_X$, then again there is no incentive to produce at this next level. This situation corresponds to one where the unit operating cost becomes higher at a higher output level. Such could occur when the capacity of the machine which provides the previously cheaper unit operating cost is reached and to achieve a higher level of output, the parts will have to be reassigned to alternative machines for more expensive machining.

Another interesting issue concerns the substitution of resources. For operations (1, 4, 2, 4) and (1, 4, 5, 4) where pooling takes place, it could be viewed that the operation by machine 2 is being substituted by machine 5; and such is still desirable as long as the total profit remains attractive. Similarly, but perhaps more indirectly, situations could take place between direct and indirect labor, or even between

Table VII.7

The Optimal Dual Variables for the Allocation Constraints

1. Indirect labor - 0
2. Direct labor - 0
3. Energy - 0
4. Maintenance labor - 0.
5. M/C Two Capacity - 0.18
6. M/C Three capacity - 0
7. M/C Four Capacity - 0
8. M/C Five Capacity - 0
9. AGV Capacity -0

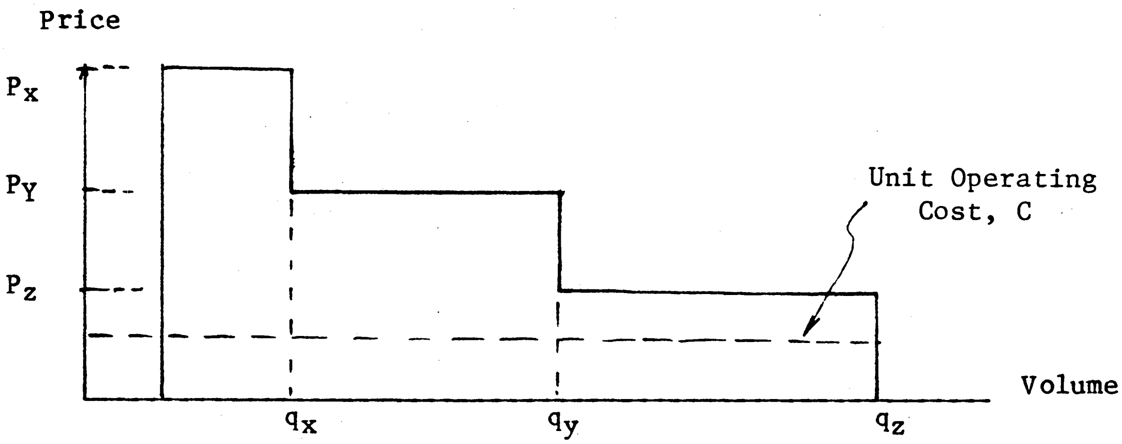


Figure VII.5a

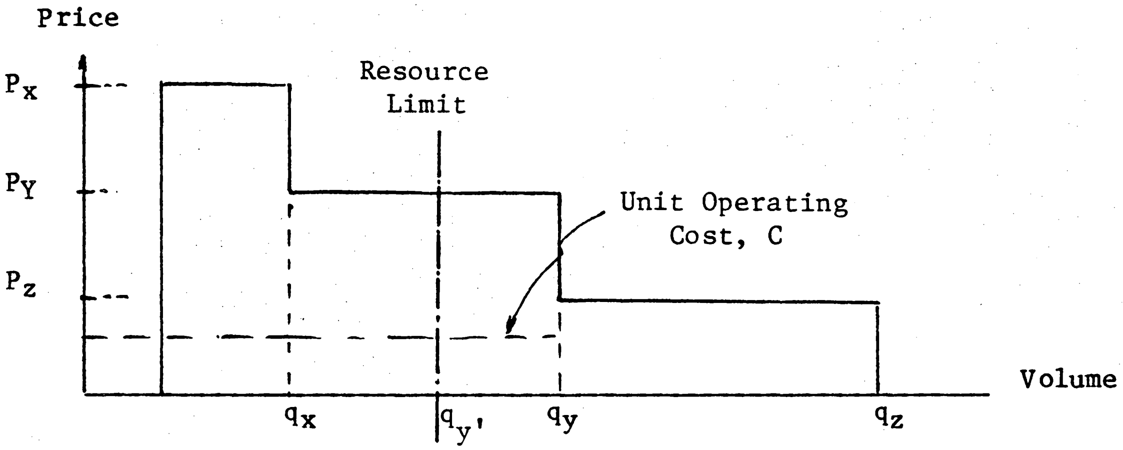


Figure VII.5b

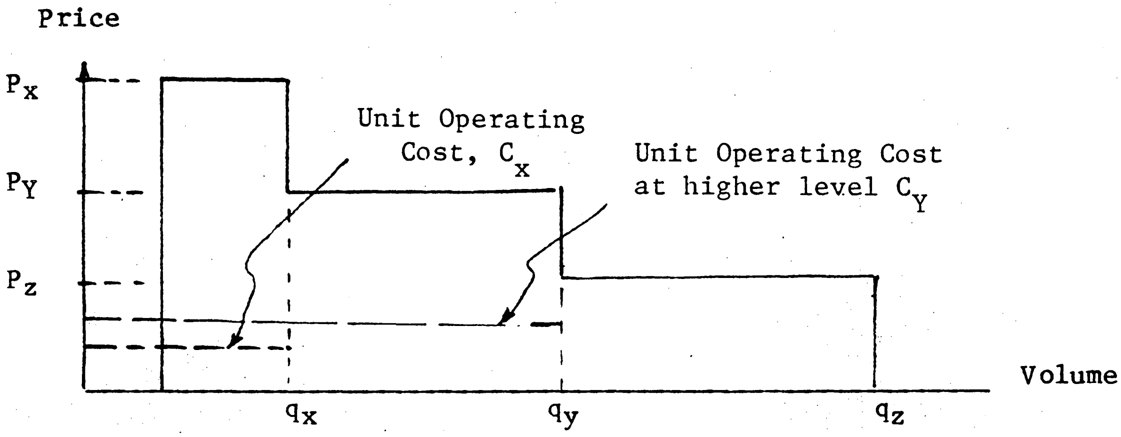


Figure VII.5c

Figures VII.5 a–c Some Revenue-Cost Relationships machine and AGV system. That is, if the resources for direct labor is limited and indirect labor abundant, then the machining operations may be re-routed in such a fashion that less direct labor is consumed while more consumption is placed upon indirect labor. Using a similar argument, consider the situation where the capacity of the AGV system is limited. Shorter routes may be more desirable even if this means higher machining costs. Of course, both of the preceding situations assume that such substitution could result in a more desirable total profit.

VII.3.4 <u>Sensitivity Analysis</u> (Also see Figure VII.7 for a summary of the following results.

VII.3.4.1 Change of AGV Capacity. The utilization rates of the respective resources at the optimal operating profit is listed in Table VII.8. To see how the capacity of the AGV affects the operating profit, instead of having two vehicles, the capacity limit for one vehicle is used. At this new limit, the optimal operating profit remains unchanged as can be deduced from the utilization rate. To go one step further, assume that the AGV capacity is 2,000,000 ft/yr. Here, the AGV limit becomes the sole binding constraint (see Table VII.9 for the dual variable). The optimal machine parts assignment are listed on Table VII.10. At this capacity limit, while part type two remains at a production level of 1600, the production levels of both part type one and part type three have decreased. Further, while part type three remains producing at the upper limit of the lower price break (higher selling price, lower production quantity), part type one cannot achieve the upper limit production level due to the AGV constraint. Also note that when the material handling constraint is the first one to become binding, pooling does not take place.

VII.3.4.2 Change of Machine Capacity. Instead of having 480,000 hr. capacity for each machine, 240,000 hrs. is used. This results in an infeasible situation. Alternatively, the capacity limits of each of the four machines are assumed to have a capacity of 360,000 hours. The resulting optimum parts assignment are shown in Table VII.11. At this production schedule, the production of part type three decireases to 2000, while the other two part types remain the same. Such phenomena parallel situations depicted in Figure VII.5c (explained previously).

VII.3.4.3 Change in demand profile. To see how the deman profile can affect the machine assignment, let the price-volume relationship be the one shown in Figure VII.6. The optimal operating profit for the new demand profile is \$815,701 (see Table VII.12). But more importantly, because of the lower price (160 to 100) as well as lower output volume (3800 to 2800), the production level for part type one is now 1400 at the selling price of \$200. That is, instead of producing at the 3rd price-break, the production level is now shifted to the 1st. This phenomena can be explained by the two situations discussed in Figures VII.5 a, VII.5c. Here, the total profit resulting from producing at the 1st price-break is now the highest, i.e, $(200)(1400) - C_1(1400) <$

Table VII.8

Respective % Consumption of Available Resources

Input Types	Unit Consumed	Unit Available	Utilization Rate
Direct Labor	600,286 HR	1,200,000 HR	5%
Indirect Labor	453,428 HR	1,200,000 HR	37.8%
Energy	679,949 KW-HR	10,000,000 KW-HR	6.8%
Maintenance	118.802 HR	600,000 HR	19.8%
Machine A	480,000 HR	480,000 HR	100%
Machine B	108,899 HR	480,000 HR	22.7%
Machine D	391,398 HR	480,000 HR	81.54%
AGV System	3,415,981 FT	72,000,000 FT	4%

Table VII.9

The Optimal Dual Variables for the Allocacation Constraints
(AGV 2,000,000 ft. per yr.)

1. Indirect labor - 0
2. Direct labor - 0
3. Energy (misc.) - 0
4. Maintenance labor - 0
5. M/C Two capacity - 0
6. M/C Three Capacity - 0
7. M/C Four Capacity - 0
8. M/C Five Capacity - 0
9. AGV Capacity - 0.23

Table VII.10

The Optimal Parts Assignment When AGV is 2,000,000.

```
THE OPTIMUM IS
   774631.937


THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

         P     K     M     S        OBJ.      Y(P,K,M,S)
                                    COEFF.

  1      1     1     2     1        20.94     1376.47
  2      1     1     3     1        23.71        0.00
  3      1     2     4     2        16.50     1376.47
  4      1     2     4     3        19.17        0.0
  5      1     3     3     4        16.71        0.00
  6      1     3     4     4         6.80     1376.46
  7      1     3     5     4        21.98        0.0
  8      1     4     2     3        15.79        0.0
  9      1     4     2     4        21.12     1376.46
 10      1     4     2     5        23.79        0.0
 11      1     4     5     3        25.29        0.0
 12      1     4     5     4        30.62        0.0
 13      1     4     5     5        17.29        0.00
 14      1     5     4     2        20.75        0.00
 15      1     5     4     5        15.42        0.0
 16      1     5     5     2        16.75     1376.47
 17      1     5     5     5        11.41        0.00
 18      1     6     1     4        10.67        0.0
 19      1     6     1     5        13.33     1376.47
 20      1     6     1     1      -200.00     1376.47
 21      2     1     3     1        59.89     1600.00
 22      2     2     2     3        21.20     1600.00
 23      2     2     3     3        43.33        0.0
 24      2     3     2     2         8.38     1600.00
 25      2     3     2     3        11.04        0.00
 26      2     3     3     2        35.00        0.0
 27      2     3     3     3        21.67        0.0
 28      2     3     4     2        20.75        0.0
 29      2     3     4     3        23.42        0.0
 30      2     4     4     2        42.00        0.0
 31      2     4     4     3        44.67        0.0
 32      2     4     4     4        34.00        0.00
 33      2     4     5     2        30.79     1600.00
 34      2     4     5     3        33.45        0.00
 35      2     4     5     4        38.79        0.0
 36      2     5     4     4        29.75        0.00
 37      2     5     4     5        32.42        0.00
 38      2     5     5     4        39.89        0.0
 39      2     5     5     5        26.56     1600.00
 40      2     6     2     4        16.10        0.0
 41      2     6     2     5        18.76     1600.00
 42      2     6     5     4        23.71        0.0
 43      2     6     5     5        10.37        0.0
 44      2     7     1     2         2.67     1600.00
 45      2     7     1     5        13.33        0.00
 46      2     7     1     1      -250.00     1600.00
 47      3     1     2     1        30.93     2000.00
 48      3     1     3     1        45.37        0.0
 49      3     2     2     2        17.87     2000.00
 50      3     2     2     3        20.53        0.00
 51      3     2     4     2        42.00        0.0
 52      3     2     4     3        44.67        0.0
 53      3     2     5     2        29.40        0.0
 54      3     2     5     3        32.07        0.0
 55      3     3     4     2        20.75     2000.00
 56      3     3     4     4        12.75        0.00
 57      3     3     4     5        15.42        0.00
 58      3     4     2     4        13.58     1999.99
 59      3     4     3     4        16.17        0.00
 60      3     5     3     2        46.48        0.0
 61      3     5     3     3        33.15        0.00
 62      3     5     5     2        22.62     2000.00
 63      3     5     5     3        25.29        0.0
 64      3     6     4     3        19.17        0.0
 65      3     6     4     5        11.17        0.0
 66      3     6     5     3        14.50        0.0
 67      3     6     5     5         6.50     2000.00
 68      3     7     2     4        19.17        0.00
 69      3     7     2     5        21.83     2000.00
 70      3     7     3     4        27.00        0.0
 71      3     7     3     5        29.67        0.0
 72      3     8     2     2        10.05     2000.00
 73      3     8     2     3        12.72        0.00
 74      3     8     4     2        22.45        0.0
 75      3     8     4     3        25.12        0.0
 76      3     9     2     2         3.24     2000.00
 77      3     9     2     4        11.24        0.00
 78      3     9     3     2        18.75        0.0
 79      3     9     3     4        10.75        0.0
 80      3    10     1     2         2.67     2000.00
 81      3    10     1     3         5.33        0.00
 82      3    10     1     1      -400.00     2000.00
```

$(150)(2000) - C_2(2000) < (100)(2800) - C_3(2800)$, where C_1, C_2 and C_3 are the respective unit operating costs at the upper limits of respective price breaks and $C_1 \leq C_2 \leq C_3$. Apparently before the demand profile is changed, the reverse is true: i.e. $(200)(1400) - C_1(1400) < (180)(2400) - C_2(2400) < (160)(3800) - C_3(3800)$.

VIII.4 SUMMARY

Figure VII.7 summarizes the parts assignment problems examined in this chapter. In brief, this chapter has provided the structure, the solution procedure and the problem setup for the parts assignment problem. An illustrative example was also presented to help understand the relevant issues regarding the part-assignment task. In the next chapter, this assignment task will be cast in a replacement context.

Table VII.11

The Optimal Parts Assighment When Machine Capacities are All at 360,000.

The Optimum is 846856.562

```
THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

         P     K     M     S        OBJ.  Y(P,K,M,S)       40     2     6     2     4       16.10        0.00
                                  COEFF.                   41     2     6     2     5       18.76         0.0
                                                           42     2     6     5     4       23.71         0.0
                                                           43     2     6     5     5       10.37     1600.00
   1     1     1     2     1       20.94     3799.99       44     2     7     1     2        2.67         0.0
   2     1     1     3     1       23.71        0.00       45     2     7     1     5       13.33     1600.00
   3     1     2     4     2       16.50     3799.99       46     2     7     1     1     -250.00     1600.00
   4     1     2     4     3       19.17         0.0       47     3     1     2     1       30.93     1999.99
   5     1     3     3     4       16.71        0.00       48     3     1     3     1       45.37        0.00
   6     1     3     4     4        6.80     3800.00       49     3     2     2     2       17.87     1023.76
   7     1     3     5     4       21.98         0.0       50     3     2     2     3       20.53         0.0
   8     1     4     2     3       15.79         0.0       51     3     2     4     2       42.00         0.0
   9     1     4     2     4       21.12         0.0       52     3     2     4     3       44.67         0.0
  10     1     4     2     5       23.79         0.0       53     3     2     5     2       29.40      976.23
  11     1     4     5     3       25.29         0.0       54     3     2     5     3       32.07         0.0
  12     1     4     5     4       30.62     3800.00       55     3     3     4     2       20.75     1023.76
  13     1     4     5     5       17.29        0.00       56     3     3     4     4       12.75        0.00
  14     1     5     4     2       20.75        0.00       57     3     3     4     5       15.42      976.22
  15     1     5     4     5       15.42     2714.71       58     3     4     2     4       13.58     1999.99
  16     1     5     5     2       16.75         0.0       59     3     4     3     4       16.17         0.0
  17     1     5     5     5       11.41     1085.29       60     3     5     3     2       46.48         0.0
  18     1     6     1     4       10.67     2714.71       61     3     5     3     3       33.15         0.0
  19     1     6     1     5       13.33     1085.29       62     3     5     5     2       22.62     1999.99
  20     1     6     1     1     -160.00     3800.00       63     3     5     5     3       25.29         0.0
  21     2     1     3     1       59.89     1600.00       64     3     6     4     3       19.17       -0.00
  22     2     2     2     3       21.20     1600.00       65     3     6     4     5       11.17        0.00
  23     2     2     3     3       43.33         0.0       66     3     6     5     3       14.50         0.0
  24     2     3     2     2        8.38     1600.00       67     3     6     5     5        6.50     1999.99
  25     2     3     2     3       11.04        0.00       68     3     7     2     4       19.17         0.0
  26     2     3     3     2       35.00         0.0       69     3     7     2     5       21.83     1999.99
  27     2     3     3     3       21.67         0.0       70     3     7     3     4       27.00         0.0
  28     2     3     4     2       20.75         0.0       71     3     7     3     5       29.67         0.0
  29     2     3     4     3       23.42         0.0       72     3     8     2     2       10.05     1999.99
  30     2     4     4     2       42.00        0.00       73     3     8     2     3       12.72       -0.00
  31     2     4     4     3       44.67         0.0       74     3     8     4     2       22.45         0.0
  32     2     4     4     4       34.00        0.00       75     3     8     4     3       25.12         0.0
  33     2     4     5     2       30.79     1600.00       76     3     9     2     2        3.24     1999.99
  34     2     4     5     3       33.45        0.00       77     3     9     2     4       11.24        0.00
  35     2     4     5     4       38.79         0.0       78     3     9     3     2       18.75         0.0
  36     2     5     4     4       29.75         0.0       79     3     9     3     4       10.75         0.0
  37     2     5     4     5       32.42        0.00       80     3    10     1     2        2.67     1999.99
  38     2     5     5     4       39.89         0.0       81     3    10     1     3        5.33        0.00
  39     2     5     5     5       26.56     1600.00       82     3    10     1     1     -400.00     2000.00
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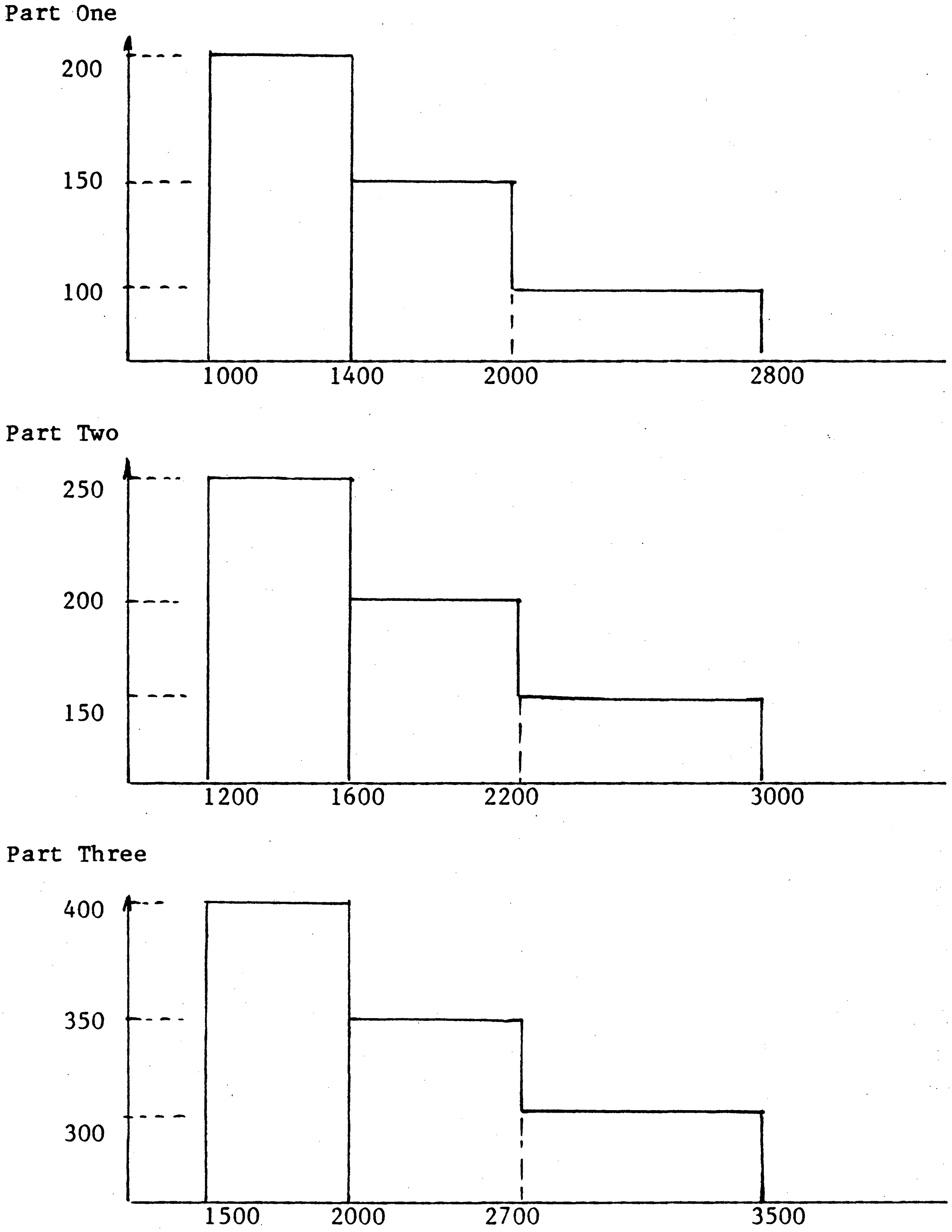


Figure VII.6

A New Demand Profile

Table VII.12

Optimal Assignment with Different Demand Profile

```
The Optimum is 815701.750
THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

        P     K     M     S      OBJ.      Y(P,K,M,S)
                                 COEFF.

 1      1     1     2     1      20.94     1399.99
 2      1     1     3     1      23.71        0.0
 3      1     2     4     2      16.50     1399.99
 4      1     2     4     3      19.17       -0.00
 5      1     3     3     4      16.71        0.00
 6      1     3     4     4       6.80     1400.00
 7      1     3     5     4      21.98        0.0
 8      1     4     2     3      15.79        0.0
 9      1     4     2     4      21.12     1399.99
10      1     4     2     5      23.79        0.0
11      1     4     5     3      25.29        0.0
12      1     4     5     4      30.62        0.0
13      1     4     5     5      17.29        0.00
14      1     5     4     2      20.75        0.00
15      1     5     4     5      15.42        0.0
16      1     5     5     2      16.75     1399.99
17      1     5     5     5      11.41        0.00
18      1     6     1     4      10.67        0.0
19      1     6     1     5      13.33     1400.00
20      1     6     1     1    -200.00     1400.00
21      2     1     3     1      59.89     1600.00
22      2     2     2     3      21.20     1600.00
23      2     2     3     3      43.33        0.0
24      2     3     2     2       8.38     1600.00
25      2     3     2     3      11.04        0.00
26      2     3     3     2      35.00        0.0
27      2     3     3     3      21.67       -0.00
28      2     3     4     2      20.75        0.0
29      2     3     4     3      23.42        0.0
30      2     4     4     2      42.00        0.00
31      2     4     4     3      44.67        0.0
32      2     4     4     4      34.00        0.00
33      2     4     5     2      30.79     1600.00
34      2     4     5     3      33.45       -0.00
35      2     4     5     4      38.79        0.0
36      2     5     4     4      29.75        0.0
37      2     5     4     5      32.42        0.0
38      2     5     5     4      39.89        0.0
39      2     5     5     5      26.56     1600.00
40      2     6     2     4      16.10        0.00
41      2     6     2     5      18.76     1003.47
42      2     6     5     4      23.71        0.0
43      2     6     5     5      10.37      596.52
44      2     7     1     2       2.67     1003.47
45      2     7     1     5      13.33      596.52
46      2     7     1     1    -250.00     1600.00
47      3     1     2     1      30.93     2699.99
48      3     1     3     1      45.37        0.00
49      3     2     2     2      17.87     2699.99
50      3     2     2     3      20.53        0.0
51      3     2     4     2      42.00        0.0
52      3     2     4     3      44.67        0.0
53      3     2     5     2      29.40        0.0
54      3     2     5     3      32.07        0.0
55      3     3     4     2      20.75     2699.99
56      3     3     4     4      12.75        0.00
57      3     3     4     5      15.42        0.00
58      3     4     2     4      13.58     2700.00
59      3     4     3     4      16.17       -0.01
60      3     5     3     2      46.48        0.0
61      3     5     3     3      33.15        0.0
62      3     5     5     2      22.62     2700.00
63      3     5     5     3      25.29       -0.01
64      3     6     4     3      19.17        0.0
65      3     6     4     5      11.17        0.0
66      3     6     5     3      14.50        0.00
67      3     6     5     5       6.50     2699.99
68      3     7     2     4      19.17        0.00
69      3     7     2     5      21.83     2699.99
70      3     7     3     4      27.00        0.0
71      3     7     3     5      29.67        0.0
72      3     8     2     2      10.05     2700.00
73      3     8     2     3      12.72        0.00
74      3     8     4     2      22.45        0.0
75      3     8     4     3      25.12        0.0
76      3     9     2     2       3.24     2700.00
77      3     9     2     4      11.24        0.00
78      3     9     3     2      18.75        0.0
79      3     9     3     4      10.75        0.0
80      3    10     1     2       2.67     2700.00
81      3    10     1     3       5.33        0.00
82      3    10     1     1    -350.00     2700.00
```

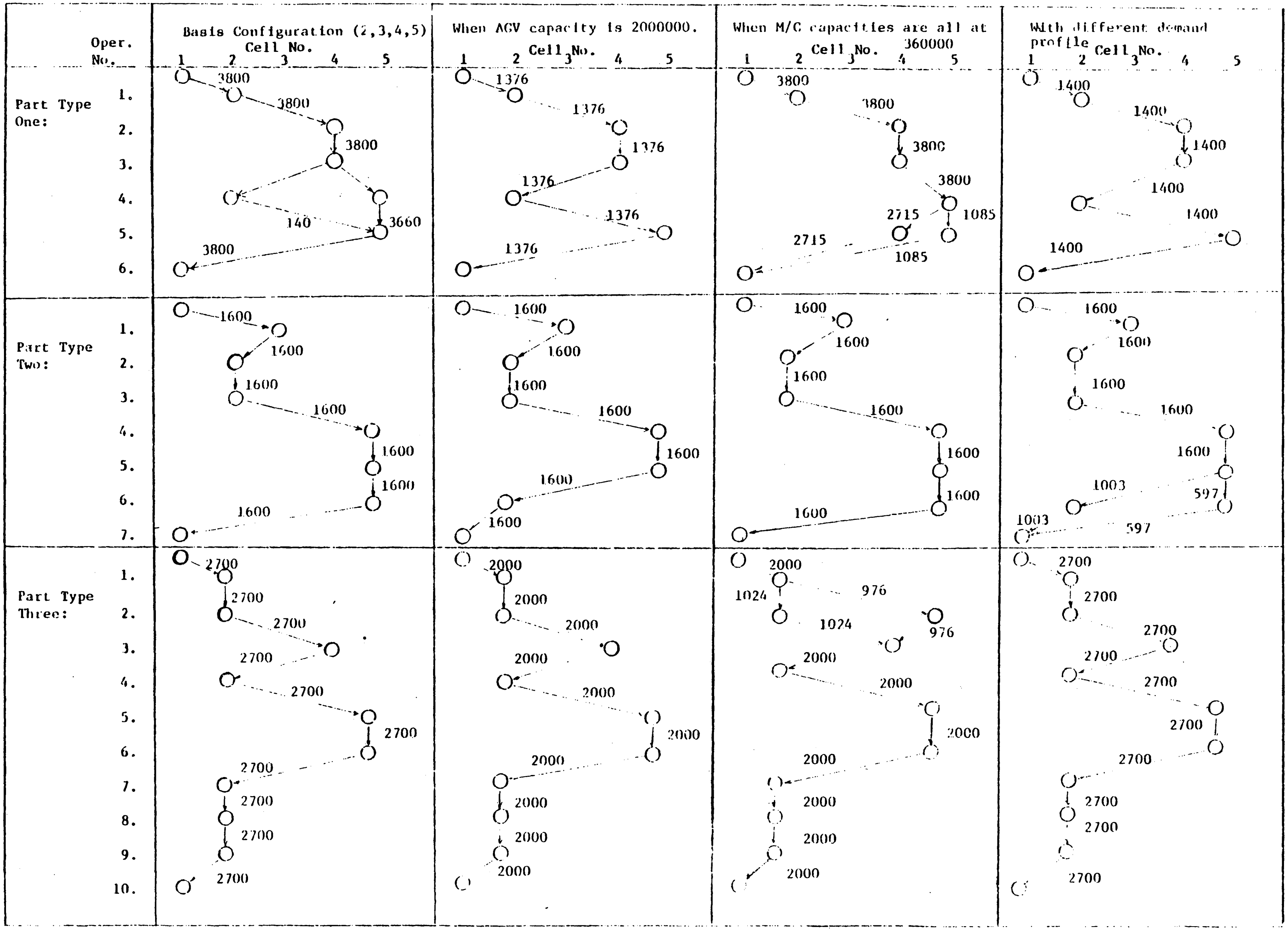


Figure VII.7 Summary of Results

CHAPTER VIII

MACHINING PARTS ASSIGNMENT IN A REPLACEMENT ENVIRONMENT - A SINGLE-YEAR ANALYSIS

VIII.1 INTRODUCTION

The previous chapter discussed the various aspects of the part assignment problem in an FMS using an illustrative example. Using the same example, this chapter extends the analysis to situations where new machine(s) are considered to replace the incumbent(s). More specifically, this section examines the general affects on the optimal parts assignment when one or all of the defenders are replaced. Let the defenders be machines A and B; and let there be two challengers, machines X and Y. The operation times per part type per machine are shown in Table VIII.1. The respective input consumption rates for the challengers are listed in Table VIII.2.

Recall that the Load/Unload station and machines A, B, C, and D are designated as machines 1, 2, 3, 4, and 5, respectively. The challengers X and Y are then identified as machines 6 and 7. Note that both challengers have relatively shorter machining times in order to reflect the capability of new machines. Also, note that each machine is capable of performing more machining operations; that is, the challengers are more flexible in general.

VIII.2 ONE-FOR-ONE REPLACEMENT SITUATIONS

There are two defenders (A,B) and as many challengers (X,Y) in this problem. Thus, there are all together four combinations of the

Table VIII.1

Operation Times Per Part Type for Challengers X and Y

Part One

Operation No.	M/C X	M/C Y
1	12.5	*
2	10.0	7.0
3	10.0	*
4	*	16.0
5	14.0	12.0
6	*	*

Part Two

Operation No.	M/C X	M/C Y
1	40.0	35.0
2	30.0	35.0
3	*	15.0
4	30.0	*
5	30.0	*
6	*	15.0
7	*	*

Part Three

Operation No.	M/C X	M/C Y
1	30.0	25.0
2	30.0	25.0
3	10.0	10.0
4	15.0	8.0
5	25.0	20.0
6	8.0	8.0
7	15.0	*
8	15.0	*
9	5.0	*
10	*	*

Table VIII.2

Respective Input Consumption Rates by the Challengers X and Y

	Direct Labor (min.)	Indirect Labor (min.)	Energy 75 KW M/C KW-HR	Maintenance (min.)
Machine X	.4	.3	.4	.1
Machine Y	.3	.25	.25	.05

one-for-one replacement nature; namely (6,3,4,5), (7,3,4,5), (2,6,4,5) and (2,7,4,5). The case where machine A (labeled as machine 2) is replaced, resulting in (6,3,4,5) and (7,3,4,5), will be discussed first followed by replacement of machine B (labeled as machine 3), resulting in (2,6,4,5) and (2,7,4,5). For sections 2, 3, and 4, see also Figure VIII.1 which summarizes the results.

VIII.2.1 FMS configurations of (6,3,4,5) and (7,3,4,5) - Replacement without expansion

Table VIII.3 lists the results of the first case. Note also that in Table VIII.3, machine 6 is being placed in station number 2 (machine cell 2) and where M equals two, the assignment is to machine 6 now occupying station number 2. From hereon, such representation of challenger(s) replacing incumbent(s) will be adopted throughout. The optimal operating profit for (6,3,4,5) is \$1,095,706, or an increase of \$198,612. The price-breaks for all three part types remained the same, implying that the more efficient machine 6 is either incapable of producing at a higher price-break range (which would produce higher total profit), or that at the higher price-break, the total resulting profit is not as attractive. In other words, expansion is not recommended even with the introduction of a new, more efficient and more flexible machine. With respect to the assignment of work, as can be expected, machine 6 picked up as much of the workload as its capacity allows. The constraint corresponding to machine 6 is binding.

For results from sections VII.2,3,4, see also Figure VIII.1 at the end of this chapter.

Table VIII.3

Optimal Parts Assignment for FMS Configuration (6,3,4,5)

```
The Optimum is    1095706.00

THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

      P    K    M    S       OBJ.      Y(P,K,M,S)
                             COEFF.

 1    1    1    2    1      16.50     3799.99
 2    1    1    3    1      23.71        0.0
 3    1    2    2    2       4.67     3799.99
 4    1    2    2    3       7.33       -0.00
 5    1    2    4    2      16.50        0.0
 6    1    2    4    3      19.17        0.0
 7    1    3    2    2       4.67       -0.01
 8    1    3    2    4      12.67        0.0
 9    1    3    3    2      24.71        0.0
10    1    3    3    4      16.71        0.0
11    1    3    4    2      14.80        0.0
12    1    3    4    4       6.80        0.00
13    1    3    5    2      13.98     3800.00
14    1    3    5    4      21.98        0.0
15    1    4    5    2      22.62       -0.01
16    1    4    5    3      25.29        0.00
17    1    4    5    4      30.62        0.00
18    1    4    5    5      17.29     3800.00
19    1    5    2    5      17.20        0.00
20    1    5    4    5      15.42       -0.00
21    1    5    5    5      11.41     3800.00
22    1    6    1    2       2.67        0.0
23    1    6    1    4      10.67       -0.00
24    1    6    1    5      13.33     3800.00
25    1    6    1    1    -160.00     3800.00
26    2    1    2    1      29.33     1600.00
27    2    1    3    1      59.89       -0.00
28    2    2    2    2      14.00     1600.00
29    2    2    2    3      16.67        0.0
30    2    2    3    2      56.67        0.0
31    2    2    3    3      43.33       -0.00
32    2    3    3    2      35.00        0.0
33    2    3    3    3      21.67       -0.00
34    2    3    4    2      20.75     1600.00
35    2    3    4    3      23.42        0.0
36    2    4    2    3      16.67        0.00
37    2    4    2    4      22.00        0.0
38    2    4    4    3      44.67        0.0
39    2    4    4    4      34.00        0.0
40    2    4    5    3      33.45       -0.00
41    2    4    5    4      38.79     1600.00
42    2    5    2    2      14.00        0.0
43    2    5    2    4      22.00        0.0
44    2    5    2    5      24.67        0.0
45    2    5    4    2      37.75        0.0
46    2    5    4    4      29.75        0.0
47    2    5    4    5      32.42        0.0
48    2    5    5    2      31.89        0.0
49    2    5    5    4      39.89        0.00
50    2    5    5    5      26.56     1600.00
51    2    6    5    2      15.71        0.00
52    2    6    5    4      23.71        0.00
53    2    6    5    5      10.37     1600.00
54    2    7    1    5      13.33     1599.99
55    2    7    1    1    -250.00     1600.00
56    3    1    2    1      24.67     2699.99
57    3    1    3    1      45.37        0.00
58    3    2    2    2      14.00      325.47
59    3    2    2    3      16.67        0.0
60    3    2    4    2      42.00        0.0
61    3    2    4    3      44.67        0.0
62    3    2    5    2      29.40     2374.52
63    3    2    5    3      32.07        0.0
64    3    3    2    2       4.67      325.47
65    3    3    2    4      12.67        0.0
66    3    3    2    5      15.33        0.0
67    3    3    4    2      20.75        0.0
68    3    3    4    4      12.75        0.00
69    3    3    4    5      15.42     2374.52
70    3    4    2    2       7.00      325.47
71    3    4    2    4      15.00        0.0
72    3    4    3    2      24.17        0.0
73    3    4    3    4      16.17     2374.52
74    3    5    2    2      11.67      325.47
75    3    5    2    3      14.33     2374.52
76    3    5    3    2      46.48        0.0
77    3    5    3    3      33.15        0.0
78    3    5    5    2      22.62        0.0
79    3    5    5    3      25.29        0.0
80    3    6    2    2       3.73     2699.99
81    3    6    2    3       6.40        0.00
82    3    6    2    5      14.40        0.0
83    3    6    4    2      16.50        0.0
84    3    6    4    3      19.17        0.0
85    3    6    4    5      11.17        0.0
86    3    6    5    2      11.83        0.0
87    3    6    5    3      14.50        0.0
```

Table VIII.3 (cont'd)

88	3	6	5	5	6.50	0.00
89	3	7	2	2	7.00	2699.99
90	3	7	2	4	15.00	0.00
91	3	7	2	5	17.67	0.00
92	3	7	3	2	35.00	0.0
93	3	7	3	4	27.00	0.0
94	3	7	3	5	29.67	0.0
95	3	8	2	2	7.00	2699.99
96	3	8	2	3	9.67	0.00
97	3	8	4	2	22.45	0.0
98	3	8	4	3	25.12	0.0
99	3	9	2	2	2.33	2699.99
100	3	9	2	4	10.33	0.0
101	3	9	3	2	18.75	0.0
102	3	9	3	4	10.75	0.00
103	3	10	1	2	2.67	2699.99
104	3	10	1	3	5.33	0.00
105	3	10	1	1	-350.00	2700.00

The optimal operating profit for (7,3,4,5) is \$1,168,156 (see Table VIII.4), \$72,450 more than that of (6,3,4,5) and \$271,062 more than that of (2,3,4,5). Configuration (7,3,4,5) is expected to perform better than (6,3,4,5). The reason is that between machines 6 and 7. While not dominating in machining times, machine 6 has lower input consumption rates. As in (6,3,4,5) a heavy workload is placed upon machine 7 and its capacity limit is also reached. The production levels of (7,3,4,5) is identical to that of (2,3,4,5) and (6,3,4,5). However, the part assignments differ.

VIII.2.2 FMS Configurations of (2,6,4,5) and (2,7,4,5) - Replacements With Expansion

Table VIII.5 lists the results for (2,6,4,5). The operating profit is \$1,216,100, the highest thus far. This result was expected for, all the machines under consideration, machine 3 has the most inferior parameters. Except for direct labor consumption rate, it has the highest consumption rates for all other inputs. Hence, replacing machine 3 by machine 6 improves the FMS operating profit significantly. Furthermore, with the removal of the inferior machine 3 coupled with the addition of the new and more flexible machine 7, the production level of part type two increases from 1600 to 2200. The demand for increased production can be explained by one or both of the following: (a) the increased efficiency enables the unit production cost to decrease, and consequently, the total profit resulting from increased production become economically attractive, (b) the added capacity allows the higher level of production and the total profit at the new level to now

Table VIII.4

Optimal Parts Assignment for FMS Configuration (7,3,4,5)

The Optimum is 1168156.00

THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

	P	K	M	S	OBJ. COEFF.	Y(P,K,M,S)
1	1	1	3	1	23.71	3799.99
2	1	2	2	3	5.09	3799.99
3	1	2	4	3	19.17	0.0
4	1	3	3	2	24.71	0.0
5	1	3	3	4	16.71	0.0
6	1	3	4	2	14.80	3800.00
7	1	3	4	4	6.80	-0.00
8	1	3	5	2	13.98	-0.01
9	1	3	5	4	21.98	0.0
10	1	4	2	3	8.20	0.00
11	1	4	2	4	13.53	3800.00
12	1	4	2	5	16.20	-0.01
13	1	4	5	3	25.29	0.0
14	1	4	5	4	30.62	0.0
15	1	4	5	5	17.29	0.0
16	1	5	2	2	4.15	3799.99
17	1	5	2	5	14.82	0.00
18	1	5	4	2	20.75	0.0
19	1	5	4	5	15.42	0.0
20	1	5	5	2	16.75	0.0
21	1	5	5	5	11.41	0.0
22	1	6	1	2	2.67	3799.99
23	1	6	1	4	10.67	0.00
24	1	6	1	5	13.33	0.00
25	1	6	1	1	-160.00	3800.00
26	2	1	2	1	22.77	1599.99
27	2	1	3	1	59.89	0.00
28	2	2	2	2	12.10	1600.00
29	2	2	2	3	14.77	0.0
30	2	2	3	2	56.67	0.00
31	2	2	3	3	43.33	0.0
32	2	3	2	2	5.19	1600.00
33	2	3	2	3	7.85	0.0
34	2	3	3	2	35.00	0.0
35	2	3	3	3	21.67	0.0
36	2	3	4	2	20.75	0.0
37	2	3	4	3	23.42	0.0
38	2	4	2	2	12.10	0.00
39	2	4	2	3	14.77	0.0
40	2	4	2	4	20.10	0.0
41	2	4	4	2	42.00	0.0
42	2	4	4	3	44.67	0.0
43	2	4	4	4	34.00	0.00
44	2	4	5	2	30.79	1599.99
45	2	4	5	3	33.45	0.00
46	2	4	5	4	38.79	0.0
47	2	5	4	2	37.75	0.0
48	2	5	4	4	29.75	0.00
49	2	5	4	5	32.42	0.00
50	2	5	5	2	31.89	0.0
51	2	5	5	4	39.89	0.0
52	2	5	5	5	26.56	1599.99
53	2	6	2	4	13.19	0.0
54	2	6	2	5	15.85	0.00
55	2	6	5	4	23.71	0.0
56	2	6	5	5	10.37	1599.99
57	2	7	1	2	2.67	0.0
58	2	7	1	5	13.33	1599.99
59	2	7	1	1	-250.00	1600.00
60	3	1	2	1	19.31	2699.99
61	3	1	3	1	45.37	0.0
62	3	2	2	2	8.65	2699.99
63	3	2	2	3	11.31	0.00
64	3	2	4	2	42.00	0.0
65	3	2	4	3	44.67	0.0
66	3	2	5	2	29.40	0.0
67	3	2	5	3	32.07	0.0
68	3	3	2	2	3.46	2699.99
69	3	3	2	4	11.46	0.00
70	3	3	2	5	14.12	0.00
71	3	3	4	2	20.75	0.0
72	3	3	4	4	12.75	0.0
73	3	3	4	5	15.42	0.0
74	3	4	2	2	2.77	2699.99
75	3	4	2	4	10.77	0.00
76	3	4	3	2	24.17	0.0
77	3	4	3	4	16.17	0.0
78	3	5	2	2	6.92	1370.00
79	3	5	2	3	9.58	0.0
80	3	5	3	2	46.48	0.0
81	3	5	3	3	33.15	0.0
82	3	5	5	2	22.62	1329.99
83	3	5	5	3	25.29	0.00
84	3	6	2	2	2.77	0.00
85	3	6	2	3	5.43	0.0
86	3	6	2	5	13.43	0.0
87	3	6	4	2	16.50	0.0

Table VIII.4 (cont'd)

88	3	6	4	3	19.17	0.0
89	3	6	4	5	11.17	0.0
90	3	6	5	2	11.83	1370.00
91	3	6	5	3	14.50	0.00
92	3	6	5	5	6.50	1329.99
93	3	7	3	2	35.00	0.0
94	3	7	3	4	27.00	0.00
95	3	7	3	5	29.67	2699.99
96	3	8	4	3	25.12	2699.99
97	3	9	3	4	10.75	2700.00
98	3	10	1	3	5.33	2700.00
99	3	10	1	1	-350.00	2700.00

Table VIII.5

Optimal Parts Assignment for FMS Configuration (2,6,4,5)

The Optimum is 1216100.00

```
THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

         P     K     M     S        OBJ.      Y(P,K,M,S)
                                    COEFF.

  1      1     1     2     1        20.94        0.0
  2      1     1     3     1        13.83     3799.99
  3      1     2     3     2        18.00        0.0
  4      1     2     3     3         4.67     3799.99
  5      1     2     4     2        16.50        0.00
  6      1     2     4     3        19.17        0.0
  7      1     3     3     3         4.67     3799.99
  8      1     3     3     4        10.00        0.0
  9      1     3     4     3        17.47        0.0
 10      1     3     4     4         6.80        0.00
 11      1     3     5     3        16.65        0.0
 12      1     3     5     4        21.98        0.0
 13      1     4     2     3        15.79     3799.99
 14      1     4     2     4        21.12        0.00
 15      1     4     2     5        23.79        0.0
 16      1     4     5     3        25.29        0.0
 17      1     4     5     4        30.62        0.0
 18      1     4     5     5        17.29        0.00
 19      1     5     3     2        19.87       -0.00
 20      1     5     3     5        14.53        0.0
 21      1     5     4     2        20.75        0.0
 22      1     5     4     5        15.42        0.0
 23      1     5     5     2        16.75     3800.00
 24      1     5     5     5        11.41        0.00
 25      1     6     1     3         5.33       -0.00
 26      1     6     1     4        10.67        0.00
 27      1     6     1     5        13.33     3800.00
 28      1     6     1     1      -160.00     3800.00
 29      2     1     3     1        26.67     2199.99
 30      2     2     2     3        21.20     2199.99
 31      2     2     3     3        14.00        0.0
 32      2     3     2     2         8.38     2199.99
 33      2     3     2     3        11.04        0.00
 34      2     3     4     2        20.75        0.0
 35      2     3     4     3        23.42        0.0
 36      2     4     3     2        27.33        0.0
 37      2     4     3     4        19.33        0.00
 38      2     4     4     2        42.00        0.0
 39      2     4     4     4        34.00        0.0
 40      2     4     5     2        30.79     2200.00
 41      2     4     5     4        38.79        0.0
 42      2     5     3     3        14.00        0.00
 43      2     5     3     4        19.33        0.00
 44      2     5     3     5        22.00       -0.00
 45      2     5     4     3        40.42        0.0
 46      2     5     4     4        29.75        0.0
 47      2     5     4     5        32.42        0.0
 48      2     5     5     3        34.56        0.0
 49      2     5     5     4        39.89        0.0
 50      2     5     5     5        26.56     2200.00
 51      2     6     2     3        10.76       -0.01
 52      2     6     2     4        16.10        0.00
 53      2     6     2     5        18.76     2200.00
 54      2     6     5     3        18.37        0.0
 55      2     6     5     4        23.71        0.0
 56      2     6     5     5        10.37        0.0
 57      2     7     1     2         2.67     2200.00
 58      2     7     1     5        13.33        0.00
 59      2     7     1     1      -225.00     2200.00
 60      3     1     2     1        30.93      834.99
 61      3     1     3     1        22.00     1865.00
 62      3     2     2     2        17.87      834.99
 63      3     2     2     3        20.53        0.0
 64      3     2     3     2        27.33        0.0
 65      3     2     3     3        14.00     1865.00
 66      3     2     4     2        42.00        0.0
 67      3     2     4     3        44.67        0.0
 68      3     2     5     2        29.40        0.0
 69      3     2     5     3        32.07        0.0
 70      3     3     3     2        18.00      834.99
 71      3     3     3     3         4.67     1865.00
 72      3     3     3     4        10.00        0.0
 73      3     3     3     5        12.67       -0.00
 74      3     3     4     2        20.75        0.0
 75      3     3     4     3        23.42        0.0
 76      3     3     4     4        12.75        0.00
 77      3     3     4     5        15.42        0.00
 78      3     4     2     3         8.25       -0.00
 79      3     4     2     4        13.58        0.0
 80      3     4     3     3         7.00     2700.00
 81      3     4     3     4        12.33        0.0
 82      3     5     3     2        25.00        0.0
 83      3     5     3     3        11.67     2700.00
 84      3     5     5     2        22.62       -0.01
 85      3     5     5     3        25.29        0.0
 86      3     6     3     3         3.73     2700.00
 87      3     6     3     5        11.73        0.0
```

Table VIII.5 (cont'd)

88	3	6	4	3	19.17	0.0
89	3	6	4	5	11.17	0.0
90	3	6	5	3	14.50	0.0
91	3	6	5	5	6.50	-0.01
92	3	7	2	3	13.83	2700.00
93	3	7	2	4	19.17	0.00
94	3	7	2	5	21.83	-0.01
95	3	7	3	3	7.00	0.0
96	3	7	3	4	12.33	0.0
97	3	7	3	5	15.00	0.00
98	3	8	2	2	10.05	2700.00
99	3	8	2	3	12.72	0.0
101	3	8	3	2	20.33	0.0
102	3	8	3	3	7.00	0.0
103	3	8	4	2	22.45	0.0
104	3	8	4	3	25.12	0.0
105	3	9	2	2	3.24	2699.99
106	3	9	2	3	5.90	0.00
107	3	9	2	4	11.24	0.00
108	3	9	3	2	15.67	0.0
109	3	9	3	3	2.33	0.0
110	3	9	3	4	7.67	0.00
111	3	10	1	2	2.67	2699.99
112	3	10	1	3	5.33	0.0
113	3	10	1	1	-350.00	2700.00

becomes more desirable. Evidently, this constitutes a replacement situation whereby expansion of output is recommended.

Table VIII.6 lists the results for (2,7,4,5). This configuration results in an even higher operating profit: $1,347,463. Similar to the preceding (2,6,4,5), expansion of output level also takes place with increased production of part type two from 1600 to 2200. In many respect, this configuration is similar to configuration (2,6,4,5).

VIII.3 ONE-FOR-TWO REPLACEMENT SITUATIONS - REPLACEMENT WITH CONTRACTION

Since there are two challengers and each individually could replace both defenders, there exists two possible configurations of the one-for-two case, the two configurations are (6,4,5) and (7,4,5).

VIII.3.1 FMS Configuration (6,4,5)

Table VIII.7 lists the results for (6,4,5). Note that machine 6 is placed in cell number two with cell number three left vancant. The optimal operating profit is $1,035,476 which, although the least of all new FMS configurations, is $138,382 more than the status quo configuration. The production levels for part type one decreases from 3800 to 2400 and part type three from 2700 to 2000, while the production level of part type two remains the same. At optimality, the capacity limit of machine 6 is reached. The reasons for the contraction of output parallel those for expansion. The interesting fact remains that such contraction resulted in a higher profit than the status quo.

Table VIII.6

Optimal Parts Assignment for FMS Configuration (2,7,4,5)

```
The Optimum is 1347463.00

 THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

        P     K     M     S          OBJ.       Y(P,K,M,S)
                                     COEFF.

  1     1     1     2     1          20.94      3799.99
  2     1     2     3     2          15.75        -0.00
  3     1     2     4     2          16.50      3800.00
  4     1     3     4     3          17.47        -0.00
  5     1     3     4     4           6.80      3800.00
  6     1     3     5     3          16.65        -0.00
  7     1     3     5     4          21.98         0.0
  8     1     4     2     4          21.12         0.0
  9     1     4     2     5          23.79         0.0
 10     1     4     3     4          10.87      3800.00
 11     1     4     3     5          13.53         0.0
 12     1     4     5     4          30.62         0.0
 13     1     4     5     5          17.29        -0.00
 14     1     5     3     2          17.48         0.0
 15     1     5     3     3           4.15      3800.00
 16     1     5     3     5          12.15         0.0
 17     1     5     4     2          20.75         0.0
 18     1     5     4     3          23.42         0.0
 19     1     5     4     5          15.42         0.0
 20     1     5     5     2          16.75         0.00
 21     1     5     5     3          19.41         0.0
 22     1     5     5     5          11.41        -0.00
 23     1     6     1     3           5.33      3800.00
 24     1     6     1     4          10.67        -0.00
 25     1     6     1     5          13.33        -0.00
 26     1     6     1     1        -160.00      3800.00
 27     2     1     3     1          20.10      2200.00
 28     2     2     2     3          21.20      2200.00
 29     2     2     3     3          12.10         0.00
 30     2     3     2     2           8.38      2199.99
 31     2     3     2     3          11.04         0.0
 32     2     3     3     2          18.52         0.00
 33     2     3     3     3           5.19         0.0
 34     2     3     4     2          20.75         0.0
 35     2     3     4     3          23.42         0.0
 36     2     4     3     2          25.44         0.00
 37     2     4     3     3          12.10         0.0
 38     2     4     3     4          17.44        -0.00
 39     2     4     4     2          42.00         0.0
 40     2     4     4     3          44.67         0.0
 41     2     4     4     4          34.00         0.0
 42     2     4     5     2          30.79      2200.00
 43     2     4     5     3          33.45         0.0
 44     2     4     5     4          38.79         0.0
 45     2     5     4     3          40.42         0.0
 46     2     5     4     4          29.75        -0.00
 47     2     5     4     5          32.42         0.01
 48     2     5     5     3          34.56         0.0
 49     2     5     5     4          39.89         0.0
 50     2     5     5     5          26.56      2199.99
 51     2     6     2     4          16.10         0.0
 52     2     6     2     5          18.76      2199.99
 53     2     6     3     4          10.52         0.0
 54     2     6     3     5          13.19         0.0
 55     2     6     5     4          23.71         0.0
 56     2     6     5     5          10.37         0.0
 57     2     7     1     2           2.67      2199.99
 58     2     7     1     3           5.33        -0.00
 59     2     7     1     5          13.33        -0.00
 60     2     7     1     1        -225.00      2200.00
 61     3     1     2     1          30.93       787.97
 62     3     1     3     1          16.65      2712.02
 63     3     2     2     2          17.87       787.97
 64     3     2     2     3          20.53         0.0
 65     3     2     3     2          21.98         0.0
 66     3     2     3     3           8.65      2712.02
 67     3     2     4     2          42.00         0.0
 68     3     2     4     3          44.67         0.0
 69     3     2     5     2          29.40         0.0
 70     3     2     5     3          32.07         0.0
 71     3     3     3     2          16.79       787.97
 72     3     3     3     3           3.46      2712.03
 73     3     3     3     4           8.79        -0.00
 74     3     3     3     5          11.46        -0.00
 75     3     3     4     2          20.75         0.0
 76     3     3     4     3          23.42         0.0
 77     3     3     4     4          12.75         0.0
 78     3     3     4     5          15.42         0.0
 79     3     4     2     3           8.25         0.0
 80     3     4     2     4          13.58         0.0
 81     3     4     3     3           2.77      3500.00
 82     3     4     3     4           8.10         0.00
 83     3     5     3     2          20.25         0.0
 84     3     5     3     3           6.92      3500.00
 85     3     5     5     2          22.62         0.00
 86     3     5     5     3          25.29         0.0
 87     3     6     3     3           2.77      3499.98
```

Table VIII.6 (cont'd)

88	3	6	3	5	10.77	0.0
89	3	6	4	3	19.17	0.0
90	3	6	4	5	11.17	0.0
91	3	6	5	3	14.50	0.0
92	3	6	5	5	6.50	0.00
93	3	7	2	3	13.83	3499.99
94	3	7	2	4	19.17	-0.00
95	3	7	2	5	21.83	0.00
96	3	8	2	2	10.05	3499.99
97	3	8	4	2	22.45	0.0
98	3	9	2	2	3.24	3500.00
99	3	9	2	4	11.24	0.00
100	3	10	1	2	2.67	3499.99
101	3	10	1	1	-300.00	3500.00

Table VIII.7

Optimal Parts Assignment for FMS Configuration (6,4,5)

The Optimum is 1035476.37

THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

	P	K	M	S	OBJ. COEFF.	Y(P,K,M,S)
1	1	1	2	1	16.50	2400.00
2	1	2	2	2	4.67	2400.00
3	1	2	4	2	16.50	0.0
4	1	3	2	2	4.67	0.0
5	1	3	2	4	12.67	0.0
6	1	3	4	2	14.80	0.0
7	1	3	4	4	6.80	-0.00
8	1	3	5	2	13.98	2400.00
9	1	3	5	4	21.98	0.0
10	1	4	5	2	22.62	0.00
11	1	4	5	4	30.62	0.00
12	1	4	5	5	17.29	2400.00
13	1	5	2	5	17.20	-0.00
14	1	5	4	5	15.42	0.0
15	1	5	5	5	11.41	2400.00
16	1	6	1	2	2.67	-0.00
17	1	6	1	4	10.67	0.00
18	1	6	1	5	13.33	2400.00
19	1	6	1	1	-180.00	2400.00
20	2	1	2	1	29.33	1600.00
21	2	2	2	2	14.00	1600.00
22	2	3	4	2	20.75	1600.00
23	2	4	2	4	22.00	133.34
24	2	4	4	4	34.00	0.0
25	2	4	5	4	38.79	1466.66
26	2	5	2	2	14.00	133.34
27	2	5	2	4	22.00	0.00
28	2	5	2	5	24.67	0.0
29	2	5	4	2	37.75	0.0
30	2	5	4	4	29.75	0.0
31	2	5	4	5	32.42	0.0
32	2	5	5	2	31.89	0.0
33	2	5	5	4	39.89	0.0
34	2	5	5	5	26.56	1466.66
35	2	6	5	2	15.71	133.34
36	2	6	5	4	23.71	0.00
37	2	6	5	5	10.37	1466.66
38	2	7	1	5	13.33	1600.00
39	2	7	1	1	-250.00	1600.00
40	3	1	2	1	24.67	1999.99
41	3	2	2	2	14.00	1999.99
42	3	2	4	2	42.00	0.0
43	3	2	5	2	29.40	0.00
44	3	3	2	2	4.67	1999.99
45	3	3	2	4	12.67	0.00
46	3	3	2	5	15.33	0.0
47	3	3	4	2	20.75	0.0
48	3	3	4	4	12.75	0.0
49	3	3	4	5	15.42	0.0
50	3	4	2	2	7.00	1999.99
51	3	4	2	4	15.00	0.00
52	3	5	2	2	11.67	2000.00
53	3	5	5	2	22.62	0.0
54	3	6	2	2	3.73	2000.00
55	3	6	2	5	14.40	0.0
56	3	6	4	2	16.50	0.0
57	3	6	4	5	11.17	0.0
58	3	6	5	2	11.83	0.0
59	3	6	5	5	6.50	0.00
60	3	7	2	2	7.00	2000.00
61	3	7	2	4	15.00	0.00
62	3	7	2	5	17.67	0.00
63	3	8	2	2	7.00	2000.00
64	3	8	4	2	22.45	0.0
65	3	9	2	2	2.33	2000.00
66	3	9	2	4	10.33	0.00
67	3	10	1	2	2.67	2000.00
68	3	10	1	1	-400.00	2000.00

In summary, not only can the challenger (machine 6) replace the defenders (machines 2 and 3) while maintaining a feasible parts assignment, it can also result in higher total operating profit.

VIII.3.1.1 Layout Possibility. Another intersting issue is the layout problem. In the preceding case, it is assumed that machine 6 will be placed in cell number two with cell number three vacant. What if the converse takes place? Table VIII.8 lists the results of such a configuration. The optimal operating profit is $1,035,475, virtually identical to the prior layout. The parts assignment as well as the output levels remain unchanged. The costs of certain operations, of course, changed. For example, the objective coefficient of Y_{1121}/Y_{1231} decreases from $16.5 to $13.83 since transporting to machine three from two is less costly than from one to three. On the other hand the objective coefficient of Y_{1352}/Y_{1353} increases from $13.98 to $16.65 because the distance travelled is more from machine three to machine five than it is from two to five.

Similar changes take place for product types two and three. As it turns out, the layout effect is minimal; obviously, such is not true in general. To facilitate the illustration of the entire replacement problem, from hereon, all individual challengerd which replace both defenders will be located in cell number two.

Table VIII.8

Optimal Parts Assignment for FMS Configuration (6,4,5) when M/C 6 is Placed in Cell No. Two

The Optimum is 1035475.75

```
THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

VAR   P    K    M    S       OBJ.      Y(P,K,M,S)
                             COEFF.

  1   1    1    3    1      13.83    2400.00          40   3    1    3    1      22.00     1999.99
  2   1    2    3    3       4.67    2400.00          41   3    2    3    3      14.00     1999.99
  3   1    2    4    3      19.17       0.00          42   3    2    4    3      44.67        0.0
  4   1    3    3    3       4.67       0.0           43   3    2    5    3      32.07        0.00
  5   1    3    3    4      10.00       0.0           44   3    3    3    3       4.67     1999.99
  6   1    3    4    3      17.47       0.0           45   3    3    3    4      10.00        0.00
  7   1    3    4    4       6.80       0.0           46   3    3    3    5      12.67        0.0
  8   1    3    5    3      16.65    2400.00          47   3    3    4    3      23.42        0.0
  9   1    3    5    4      21.98       0.0           48   3    3    4    4      12.75        0.0
 10   1    4    5    3      25.29       0.00          49   3    3    4    5      15.42        0.0
 11   1    4    5    4      30.62      -0.00          50   3    4    3    3       7.00     1999.99
 12   1    4    5    5      17.29    2400.00          51   3    4    3    4      12.33        0.00
 13   1    5    3    5      14.53       0.00          52   3    5    3    3      11.67     2000.00
 14   1    5    4    5      15.42       0.0           53   3    5    5    3      25.29        0.0
 15   1    5    5    5      11.41    2400.00          54   3    6    3    3       3.73     2000.00
 16   1    6    1    3       5.33       0.0           55   3    6    3    5      11.73        0.0
 17   1    6    1    4      10.67       0.00          56   3    6    4    3      19.17        0.0
 18   1    6    1    5      13.33    2400.00          57   3    6    4    5      11.17        0.0
 19   1    6    1    1    -180.00    2400.00          58   3    6    5    3      14.50        0.0
 20   2    1    3    1      26.67    1600.00          59   3    6    5    5       6.50        0.00
 21   2    2    3    3      14.00    1600.00          60   3    7    3    3       7.00     2000.00
 22   2    3    4    3      23.42    1600.00          61   3    7    3    4      12.33        0.00
 23   2    4    3    4      19.33     133.34          62   3    7    3    5      15.00        0.00
 24   2    4    4    4      34.00       0.0           63   3    8    3    3       7.00     2000.00
 25   2    4    5    4      38.79    1466.66          64   3    8    4    3      25.12        0.0
 26   2    5    3    3      14.00     133.34          65   3    9    3    3       2.33     2000.00
 27   2    5    3    4      19.33       0.0           66   3    9    3    4       7.67        0.00
 28   2    5    3    5      22.00       0.0           67   3   10    1    3       5.33     2000.00
 29   2    5    4    3      40.42       0.0           68   3   10    1    1    -400.00     2000.00
 30   2    5    4    4      29.75       0.0
 31   2    5    4    5      32.42       0.0
 32   2    5    5    3      34.56       0.0
 33   2    5    5    4      39.89       0.0
 34   2    5    5    5      26.56    1466.66
 35   2    6    5    3      18.37     133.33
 36   2    6    5    4      23.71       0.00
 37   2    6    5    5      10.37    1466.66
 38   2    7    1    5      13.33    1600.00
 39   2    7    1    1    -250.00    1600.00
```

VIII.3.2 FMS Configuration (7,4,5)

This configuration is infeasible to this problem. Here, the infeasibility arises not from any resource limitations but from the fact that no machine in configuration (7,4,5) can perform the 7th and 9th operation of part type three (see Table VIII.9). Note that machine 7 was previously a member of configuration (2,7,4,5) as well as (3,7,4,5), both of which are feasible. Clearly, infeasibility in the FMS environment is a relative issue; that is, the machine cannot be viewed as single entity but as an element of the whole system. A machine's performance needs to be evaluated on that basis. This evidence further reinforces the systems approach to the replacement problem. Furthermore, this example raises another important issue: flexibility.

VIII.3.2.1 Flexibility in a Replacement Environment. While configuration (7,4,5) is not feasible, configuration (6,4,5) is. Note that both machine 6 and machine 7 are relatively more flexible than machine 2 as well as machine 3. Between machines 6 and 7, machine 7 is relatively more efficient. However, although virtually identical on the number of machine operations each can perform, machine 6 can perform more on part type three. That is, machine 6 is more flexible than machine 7 with regard to part type three -a flexibility which the system needs. In other words, machine 6 offers the kind of flexibility which the system lacks whereas machine 7 does not -machine 7 cannot perform

Table VIII.9

Configuration (7,4,5) - Incapable of Performing Operations 7 and 9 of Part Type Three

<u>Part Type Three</u>

Cell No. Operation No.	1 (L/U Station)	2 (Machine) 7	3 (Vacant)	4 (Machine) 4	5 (Machine) 5
1	*	25.0	*	*	*
2	*	25.0	*	40.0	34.8
3	*	10.0	*	15.0	*
4	*	8.0	*	*	*
5	*	20.0	*	*	25.0
6	*	*	*	10.0	9.4
7	*	*	*	*	*
8	*	*	*	17.0	*
9	*	*	*	*	*
10	0	*	*	*	*

7th and 9th operation of part type three. Note that configuration (7,4,5) would have been a more superior choice, if the joint effort of machines 4 and 5 is able to cover the 7th and 9th operation of part type 3.

Again, flexibility is clearly a relative issue and the approach to this issue is at the system level and not at the machine level. Two assessments on flexibility are provided: (a) that a more efficient machine may be less desirable than a flexible machine and (b) that flexibility needs to be approached not in absolute but in relative terms with respective to the existing system.

VIII.4 A TWO-FOR-TWO- REPLACEMENT SITUATION

There exists only one such combination; that is, configuration (6,7,4,5). Table VIII.10 lists the results. The operating profit is $1,463,355, the highest for this problem. The joint capacity increase and efficiency improvement enables the system to operate at a higher production level and still remain economically desirable. The new production levels are 3800, 2200 and 3500 for part types one, two and three, respectively. The dual variables for the machine capacity constraints of machines 6 and 7 both show positive value indicating that both upper limits are reached. Also of interest is that more pooling took place for this configuration, possibly due to added flexibility as well as little relative difference in efficiency.

Table VIII.10

Optimal Parts Assignment for FMS Configuratiions (6,7,4,5)

The Optimum is 1453355.00

THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

	P	K	M	S	OBJ. COEFF.	Y(P,K,M,S)
1	1	1	2	1	16.50	3799.97
2	1	2	2	2	4.67	3312.89
3	1	2	3	2	15.75	0.0
4	1	2	4	2	16.50	487.09
5	1	3	2	2	4.67	0.0
6	1	3	2	3	7.33	0.0
7	1	3	2	4	12.67	0.0
8	1	3	4	2	14.80	3312.89
9	1	3	4	3	17.47	0.00
10	1	3	4	4	6.80	487.09
11	1	3	5	2	13.98	0.0
12	1	3	5	3	16.65	0.0
13	1	3	5	4	21.98	0.0
14	1	4	3	2	18.87	0.00
15	1	4	3	4	10.87	3799.98
16	1	4	3	5	13.53	0.00
17	1	4	5	2	22.62	0.0
18	1	4	5	4	30.62	0.0
19	1	4	5	5	17.29	0.0
20	1	5	2	3	9.20	3799.98
21	1	5	2	5	17.20	0.0
22	1	5	3	3	4.15	0.0
23	1	5	3	5	12.15	0.0
24	1	5	4	3	23.42	0.0
25	1	5	4	5	15.42	0.0
26	1	5	5	3	19.41	0.0
27	1	5	5	5	11.41	0.00
28	1	6	1	2	2.67	3799.99
29	1	6	1	3	5.33	0.00
30	1	6	1	4	10.67	0.00
31	1	6	1	5	13.33	0.00
32	1	6	1	1	-160.00	3800.00
33	2	1	2	1	29.33	857.17
34	2	1	3	1	20.10	1342.80
35	2	2	2	2	14.00	857.17
36	2	2	2	3	16.67	0.0
37	2	2	3	2	25.44	0.0
38	2	2	3	3	12.10	1342.80
39	2	3	3	2	18.52	0.0
40	2	3	3	3	5.19	1342.81
41	2	3	4	2	20.75	857.17
42	2	3	4	3	23.42	0.0
43	2	4	2	3	16.67	1342.81
44	2	4	2	4	22.00	857.16
45	2	4	3	3	12.10	0.0
46	2	4	3	4	17.44	0.00
47	2	4	4	3	44.67	0.0
48	2	4	4	4	34.00	0.0
49	2	4	5	3	33.45	0.0
50	2	4	5	4	38.79	0.0
51	2	5	2	2	14.00	2199.98
52	2	5	2	3	16.67	0.0
53	2	5	2	4	22.00	0.0
54	2	5	2	5	24.67	0.0
55	2	5	4	2	37.75	0.0
56	2	5	4	3	40.42	0.0
57	2	5	4	4	29.75	0.00
58	2	5	4	5	32.42	0.0
59	2	5	5	2	31.89	0.0
60	2	5	5	3	34.56	0.0
61	2	5	5	4	39.89	0.0
62	2	5	5	5	26.56	0.00
63	2	6	3	2	18.52	0.0
64	2	6	3	4	10.52	0.00
65	2	6	3	5	13.19	0.0
66	2	6	5	2	15.71	2199.98
67	2	6	5	4	23.71	0.0
68	2	6	5	5	10.37	0.00
69	2	7	1	3	5.33	0.01
70	2	7	1	5	13.33	2199.98
71	2	7	1	1	-225.00	2200.00
72	3	1	2	1	24.67	33.37
73	3	1	3	1	16.65	3466.59
74	3	2	2	2	14.00	0.0
75	3	2	2	3	16.67	0.0
76	3	2	3	2	21.98	0.0
77	3	2	3	3	8.65	3466.59
78	3	2	4	2	42.00	0.0
79	3	2	4	3	44.67	0.0
80	3	2	5	2	29.40	0.0
81	3	2	5	3	32.07	0.0
82	3	3	2	2	4.67	33.37

Table VIII.10 (cont'd)

83	3	3	2	3	7.33	0.0
84	3	3	2	4	12.67	0.0
85	3	3	2	5	15.33	0.0
86	3	3	3	2	16.79	0.0
87	3	3	3	3	3.46	3466.59
88	3	3	3	4	8.79	0.00
89	3	3	3	5	11.46	0.00
90	3	3	4	2	20.75	0.0
91	3	3	4	3	23.42	0.0
92	3	3	4	4	12.75	0.0
93	3	3	4	5	15.42	0.0
94	3	4	2	2	7.00	33.38
95	3	4	2	3	9.67	0.0
96	3	4	2	4	15.00	0.0
97	3	4	3	2	16.10	0.0
98	3	4	3	3	2.77	3466.59
99	3	4	3	4	8.10	0.00
100	3	5	2	2	11.67	33.38
101	3	5	2	3	14.33	0.0
102	3	5	3	2	20.25	0.0
103	3	5	3	3	6.92	3466.60
104	3	5	5	2	22.62	0.0
105	3	5	5	3	25.29	0.0
106	3	6	2	2	3.73	33.37
107	3	6	2	3	6.40	3466.60
108	3	6	2	5	14.40	0.0
109	3	6	3	2	16.10	0.0
110	3	6	3	3	2.77	0.0
111	3	6	3	5	10.77	0.0
112	3	6	4	2	16.50	0.0
113	3	6	4	3	19.17	0.0
114	3	6	4	5	11.17	0.0
115	3	6	5	2	11.83	0.0
116	3	6	5	3	14.50	0.0
117	3	6	5	5	6.50	0.00
118	3	7	2	2	7.00	3499.97
119	3	7	2	3	9.67	0.00
120	3	7	2	4	15.00	0.00
121	3	7	2	5	17.67	0.00
122	3	8	2	2	7.00	3499.99
123	3	8	4	2	22.45	0.0
124	3	9	2	2	2.33	3499.99
125	3	9	2	4	10.33	0.00
126	3	10	1	2	2.67	3499.99
127	3	10	1	1	-300.00	3500.00

VIII.5 SUMMARY

The general results of the illustrative example are summarized in Figure VIII.1. Three types of replacement situations took place: one-for-one, one-for-two, and two-for-two. Because of the assumption that the total number of machines in the system cannot exceed the total number for the status quo configuration, the two-for-one replacement situation did not arise.

In summary, the parts assignment problem for FMS under a replacement environment has been analyzed. Thus far, the analysis has been focused on the operating profit of the FMS. In the next chapter, the analysis will be extended to incorporate the effect of capitalized cost under taxation. Further, the example presented in this chapter will be extended to a multi-period case. Such time-dynamic elements as deterioration and obsolescence, time value of money, changing costs, changing demand ... etc. will be included.

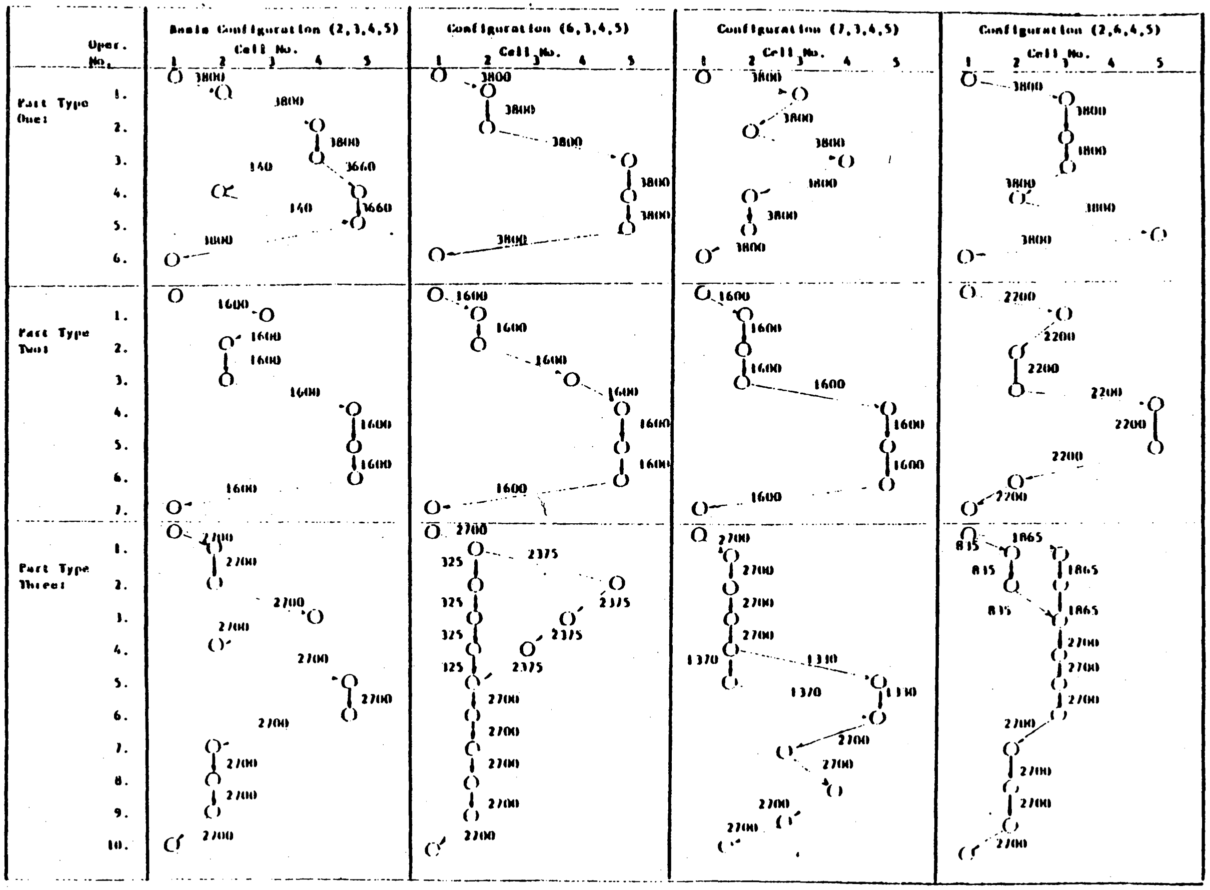


Figure VIII.1

Summary of Part Assignment of Results with Replacement Activities

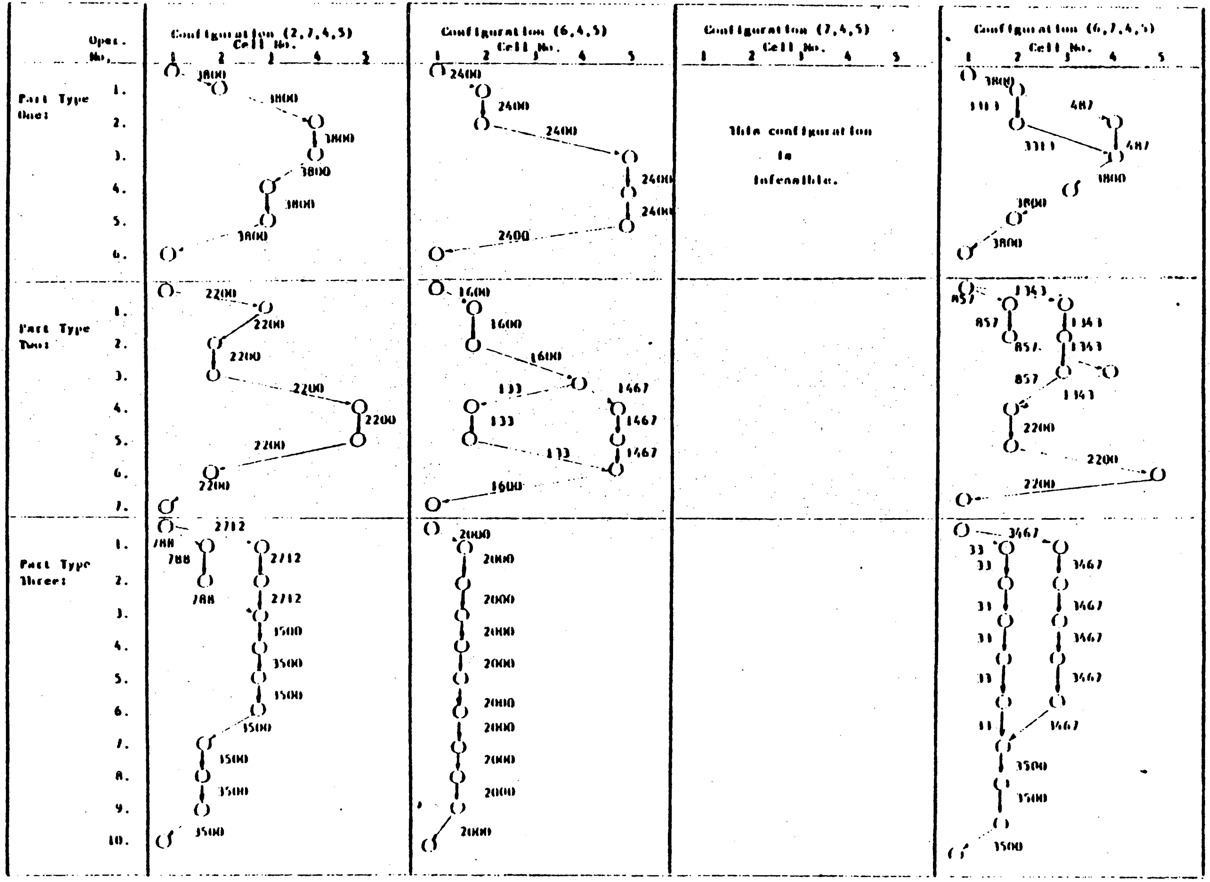


Figure VIII.1 (cont'd)

CHAPTER IX

THE OPTIMAL FMS REPLACEMENT SEQUENCE - MULTI YEAR MODEL

IX.1 INTRODUCTION

The example in the preceding chapter illustrated the vital elements of replacement decisions in an FMS environment. The replacement picture, however, is far from complete. Firstly, the consideration of capitalized costs meeds to be included. To realistically reflect the effect of capitalized costs, the analysis will be presented on an after-tax basis. Then, most importantly, the one-period analysis will be extended to the multi-period case, incorporating time-dynamic elements such as obsolescence and deterioration, time value of money, changing costs and demand, etc. In this chapter the problem structure and solution procedure for the multi-year problem is discussed first. Next, using the illustrative problem in the previous chapter and with estimated data regarding future parameters, the illustrative example is appropriately set up. The 1983 ACRS schedule is used for depreciation and, a four-year planning horizon is assumed. The final results are presented and relevant issues discussed.

IX.2 Problem Structure and Solution Procedure

IX.2.1 The Problem Structure

The dynamic programming formulation of the multi-year replacement model, as presented in Chapter VI, is sequential in nature, with each year represented by a stage in the decision sequence. At the beginning of each year, a decision is made on which FMS configuration to select. Such keep-or-replace process throughout the planning horizon forms a decision tree structure. Figure IX.1 shows a "replacement tree" with one replacement alternative at each decision point. In fact, this special tree structure corresponds to a single machine replacement problem with one challenger. Of similar nature except with more alternatives, an arbitrary FMS replacement problem is depicted in Figure IX.2 where each node represents an FMS configuration and each linking are indicates a precedence relationship between configurations. Associated with each configuration are the operating profit and capitalized cost. The optimizing task then is to determine the sequence of FMS configurations which would maximize profit for the entire production process over the planning horizon.

IX.2.2 Solution Procedure

While the dynamic programming formulation is a model in form, the logical nature of its representation can be readily translated to a solution procedure. The task then is to identify the possible configurations which could arise in a FMS replacement problem and to develop the logical decisions from year to year so as to determine the optimal replacement sequence. The FORTRAN program in Appendix III begins by generating all first-year FMS configurations. Then, the characteristics of each configuration is input to the parts assignment solution procedure (the Linear Programming Subroutine) to determine the optimal operating profit. The same steps are similarly taken for the second year and so on. Once the maximum operating profit for all configuration within the planning horizon are determined, these results are then input into the dynamic programming procedure which, after determining the capitalized cost of each configuration, would calculate the optimal replacement sequence resulting in an optimal replacement and expansion policy. Over the entire planning horizon. A general logic flow chart for this solution procedure is shown in figure IX.3.

shown in Figure IX.3

IX.2.3 Problem Size

The size of this replacement problem can be assessed by referring back to Section V.3.3, where the various combinations of defenders and challengers were discussed. In general, if the number of challengers at year t is n_t, then in year t the total number of configurations (nodes in the network or state variables in the dynamic program) is

$$TC_t = \sum_{i=1}^{d} C_i^{n_t} + \sum_{i}^{d-1} \sum_{j}^{d-i} \{C_i^{n_t} C_j^{d}\} + 1 \text{ (status quo)}; \quad n_t \geq d$$

$$TC_t = \sum_{i=1}^{n_t} C_i^{n_t} + \sum_{i}^{n_t} \sum_{j}^{d-1} \{C_i^{n_t} C_j^{d}\} + 1 \text{ (status quo)}; \quad n_t < d$$

Here, attention needs to be paid to the use of the term "challenger" which is used quite loosely. The term "challenger" is used here in the

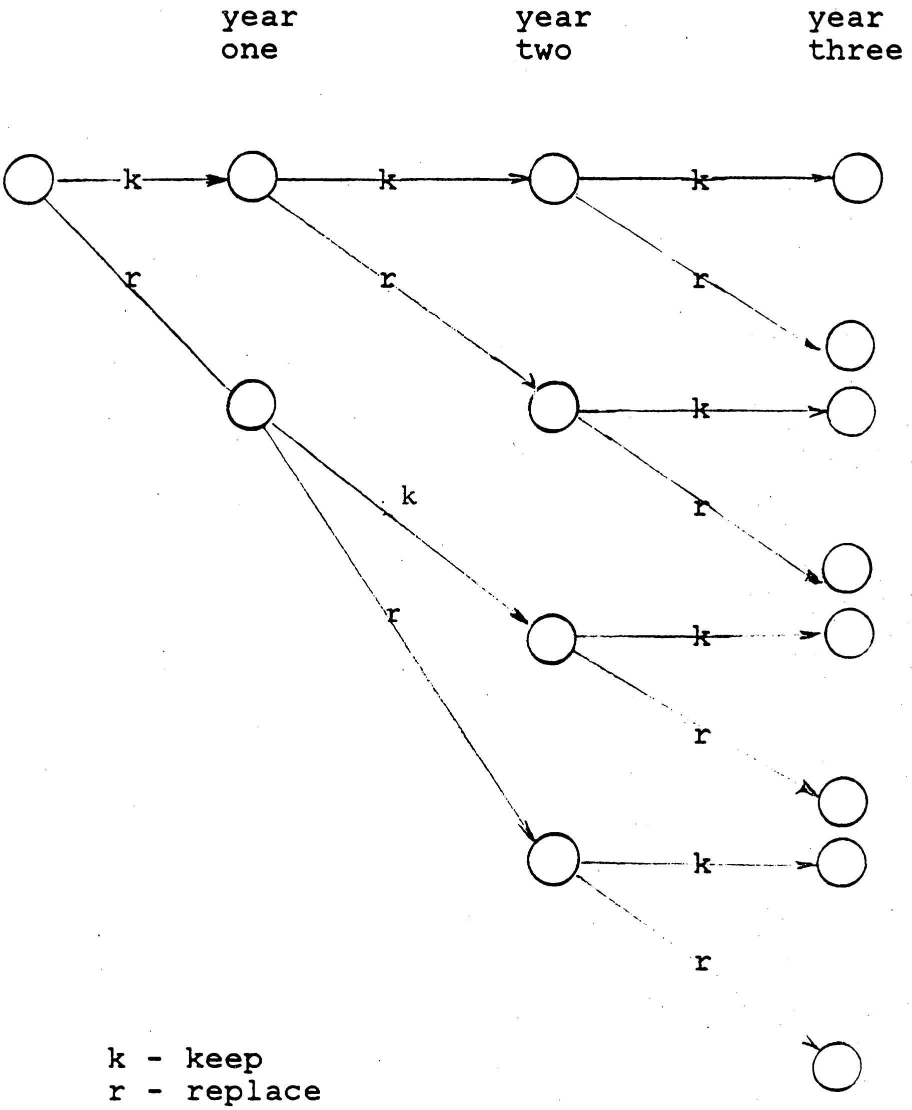


Figure IX.1

A "Replacement Tree" for Single Machine Replacement and One Challenger

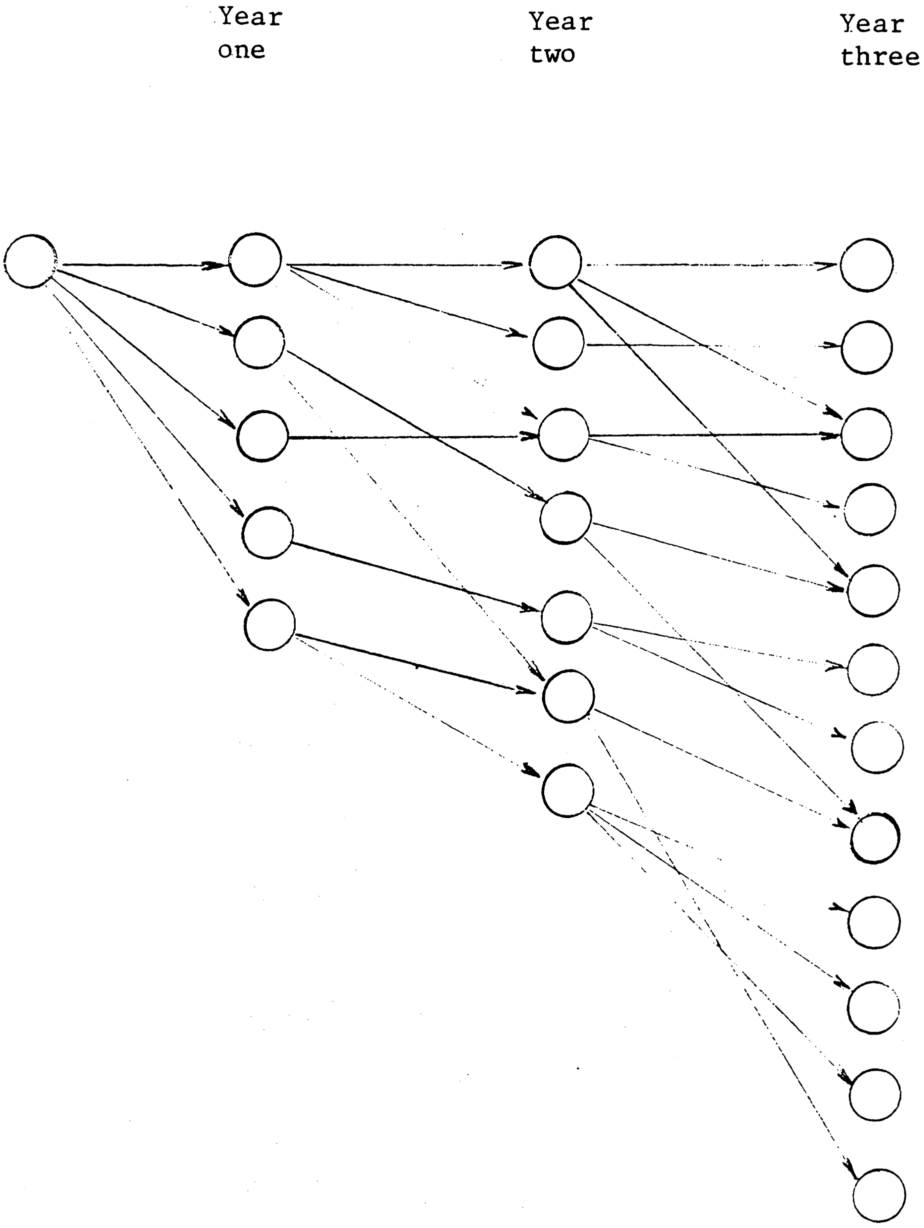


Figure IX.2

An Arbitrary FMS Replacement Tree

context that there are machines which could "show-up" in the possible configuration --they be challengers from the current year or previous years. In fact, the values n_t has the following relationships:

$$n_t = n_{t-1} + n_1 \quad \forall \quad t = 2, \ldots, T$$

That is, the total number of machines which can "show-up" in this years' configurations is equal to the total number in the preceding year plus this year's new challenger total which is an assumed value in the beginning of the planning horizon. However, the value of TC_t is still not accurate since certain combinations of "challengers" cannot take place. This comes from the assumption that once a challenger is introduced into the FMS, another machine of the same "label" (in the formulation), although of newer make, cannot be acquired. In other words, the total number of possible configurations in year t (TC_t) need to be adjusted as follows:

$$TC_t - n_t \sum_{x=0}^{t-1} x \quad \text{for both } n_t \geq d \text{ and } n_t < d$$

More specific values will be used in the illustrative example to follow.

IX.3 AN ILLUSTRATIVE EXAMPLE

The example presented in the preceding chapter is used as the setting for this multi-year illustration. Again, there are four machines in the FMS - A, B, C, and D. The defenders are machines A and

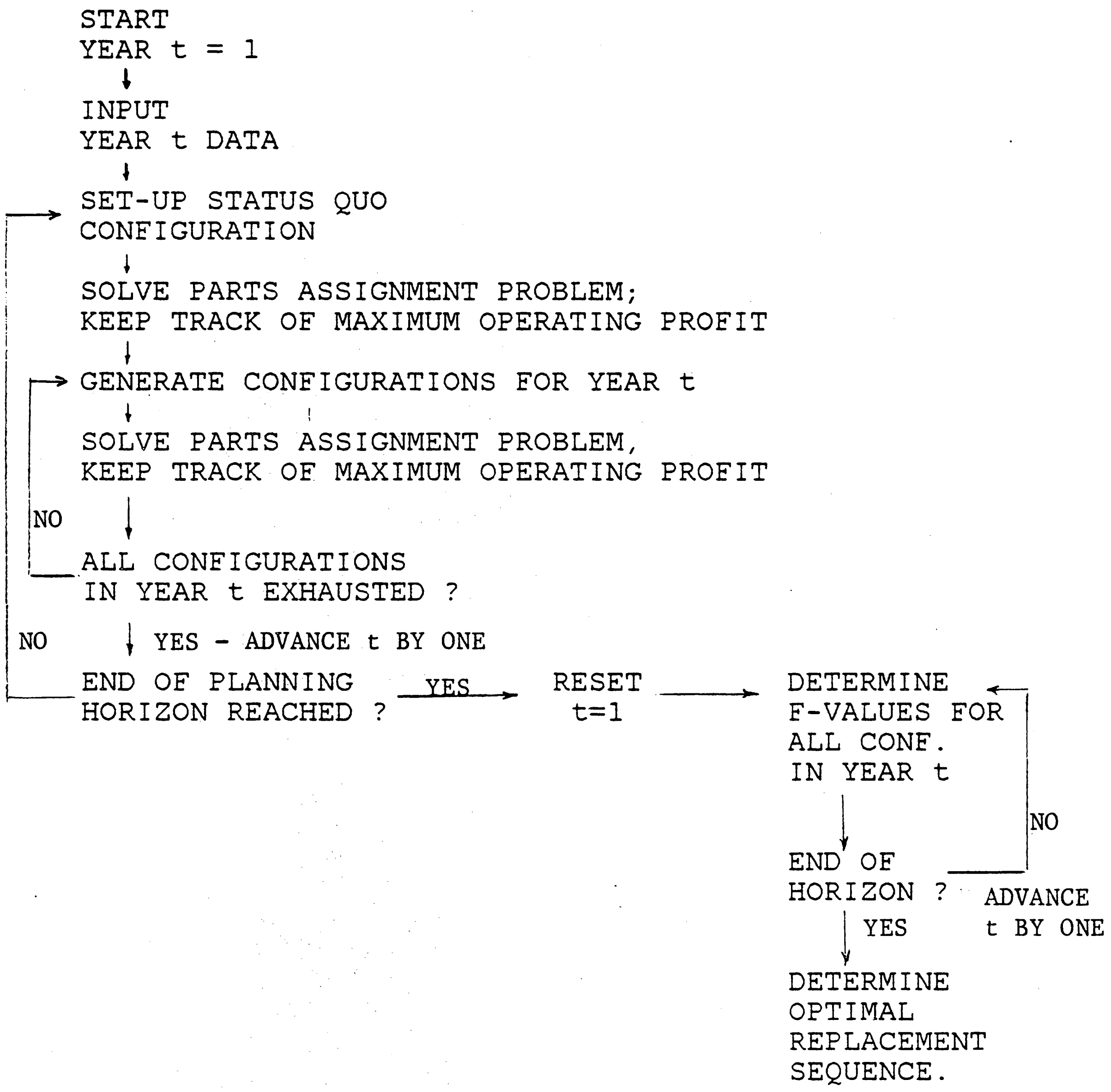


Figure IX.3

A General Logic Flow
of the Solution Procedure

B, and either or both of them are being considered for replacement by either challenger X or challenger Y, or by both. Once challenger X or Y is introduced into the FMS, it will no longer considered as replacement alternative in future years. Also, if both defenders A and B have already been replaced, this implies that complete replacement has resulted and hence no further replacement is made. The planning horizon is assumed to be four years. Table IX.1 lists the machine values over the planning horizon. Note that machines A and B are assumed to be two-year old equipment. Machine values of C and D are not included since their values will not be involved in the decision process. The market values of all machines are assumed to be equal to their book values. The 1983 ACRS schedule is used for depreciation. It should be pointed out the depreciation changes for years three and four do not follow the 1985 and 1986 ACRS schedule. Adjustments to account for these schedules requires minimal effort.

Again, to facilitate the identification process, machines involved for the entire planning horizon are labelled as

(i) defender machine A - machine 2
(ii) defender machine B - machine 3
(iii) existing machine C - machine 4
(iv) existing machine D - machine 5
(v) challenger X made in year one - machine 6
(vi) challenger Y made in year one - machine 7
(vii) challenger X made in year two - machine 8

(viii) challenger Y made in year two - machine 9

(ix) challenger X made in year three - machine 10

(x) challenger Y made in year three - machine 11

(xi) challenger X made in yaer four - machine 12

(xii) challenger Y made in year four - machine 13

Table IX.2 lists the part types demand values for the next four years. Basically, the product market is assumed to be stable with steady increase in the selling prices. The deterioration and obsolescence rates of all machines are listed in Table IX.3. The effect of machine deterioration are assumed to increase both parts operating time and input consumption rates. Similarly, the effect of machine obsolescence would decrease both parts operating times and input consumption rates. In this example problem, a uniform deterioration and obsolescence rates are applied to all machines under consideration. For example, both machines 2 and 6 have a yearly deterioration rate of 10% whereas machine 3 has a yearly deterioration rate of 15%. The unit cost of indirect labor, direct labor, energy and maintenance are expected to have a yearly increase of 6%, 8%, 7% and 7% respectively. For the unit cost of AGV, the increase is 10% per year. Lastly, the amount of resources available are identical each year (see Table VII.4 in Section VII.3.1). A time value of money of 10% is assumed.

Table IX.1

Machine Values Over the Entire Planning Horizon
(All Beginning-of-Year Values)

MACHINE NO.	2	3	6	7	8	9	10	11	12	13
YR 1.	132300	189000	500000	600000						
YR 2.	84000	126000	425000	510000	550000	660000				
YR 3.	42000	63000	315000	378000	467500	561000	605000	726000		
YR 4.	0	0	210000	252000	346500	415800	514000	617100	665500	797500
YR 5.	0	0	105000	126000	231000	277200	381150	456750	565675	677875

IX.4 PROBLEM SETUP AND PROBLEM SIZE

The data are input according to the format and order documented in the FORTRAN program. There are four decision stages (four years) in this problem. To calculate the total number of possible configurations in each year, the formula developed in the preceding section is used. For example, in year one, the total number of FMS configurations is

$$\sum_{i=1}^{2} C_i^{2} + \sum_{i}^{1} \sum_{j}^{2-i} \{C_i^{2} C_j^{2}\} + 1 - 2 \sum_{x=0}^{0} x$$

$$= (2 + 1) + (2)\ (2) + 1 = 8$$

where $d = 2$ and $n_1 = 2$. In year two, the configuration total is

$$\sum_{i=1}^{2} C_i^{4} + \sum_{i}^{1} \sum_{j}^{2-i} \{C_i^{4} C_j^{2}\} + 1 - 2 \sum_{x=0}^{1} x$$

$$= (4 + 6) + (4)\ (2) + 1 - 2 = 17$$

Similarly, the total number of configurations for years three and four are 38 and 41. All together, there are (8 + 17 + 28 + 41) = 94 configurations in this four-year problem. Since for each configuration there are 27 price-break combinations for the three part types, this replacement problem may need to solve the parts assignment sub-problem a maximum of 2583 times. Structurally, this warrants solving 2583 linear programs each of about 100 variables and 60 constraints. Some computational aspects are documented in Appendix __. Meanwhile, the 94 configurations and the machining units which each configuration are

Table IX.2

Demand Profile for Years 2, 3, and 4

A. PART TYPE ONE:

		PRODUCTION VOLUME		
		1000-1400	1401-2400	2401-3800
SELLING	YR. 2	250	230	210
PRICE	YR. 3	300	280	260
PER YR.	YR. 4	350	330	310

B. PART TYPE TWO:

		PRODUCTION VOLUME		
		1200-1600	1601-2200	2201-3000
SELLING	YR. 2	300	275	250
PRICE	YR. 3	350	325	300
PER YR.	YR. 4	400	375	350

C. PART TYPE THREE:

		PRODUCTION VOLUME		
		1500-2000	2001-2700	2701-3500
SELLING	YR. 2	450	400	350
PRICE	YR. 3	500	450	400
PER YR.	YR. 4	550	500	450

Table IX.3

Yearly Deterioration and Obsolescence Rates for Respective Machines

A. MACHINE DETERIORATION PER MACHINE EACH YEAR.

(I) PERCENTAGE INCREASE IN PARTS OPERATING TIME:

MACHINE NO.	2	3	4	5	6	7	8	9	10	11	12	13
YR 1.	10	15	10	10	10	10						
YR 2.	10	15	10	10	10	10	10	10				
YR 3.	10	15	10	10	10	10	10	10	10	10		
YR 4.	10	15	10	10	10	10	10	10	10	10	10	10

(II) PERCENTAGE INCREASE IN INPUT CONSUMPTION RATES :
(FOR ALL INPUTS)

MACHINE NO.	2	3	4	5	6	7	8	9	10	11	12	13
YR 1.	10	15	10	10	10	10						
YR 2.	10	15	10	10	10	10	10	10				
YR 3.	10	15	10	10	10	10	10	10	10	10		
YR 4.	10	15	10	10	10	10	10	10	10	10	10	10

B. MACHINE OBSOLESCENCE PER CHALLENGER EACH YEAR.

(I) PERCENTAGE DECREASE IN PARTS OPERATING TIME:

MACHINE NO.	6	7	8	9	10	11	12	13
YR 1.	5	5						
YR 2.	*	*	5	5				
YR 3.	*	*	*	*	5	5		
YR 4.	*	*	*	*	*	*	5	5

(II) PERCENTAGE DECREASE IN INPUT CONSUMPTION RATES:
(FOR ALL INPUTS)

MACHINE NO.	6	7	8	9	10	11	12	13
YR 1.	5	5						
YR 2.	*	*	5	5				
YR 3.	*	*	*	*	5	5		
YR 4.	*	*	*	*	*	*	5	5

listed in Table IX.4. A sample of the replacement tree is also shown in Figure IX.4.

For example, the path of {status-quo -(2) -(45) -(21) -(27)} would represent replacing defender A by challenger X in year one, then replacing defender B by challenger Y in year two and in years three and four, there would be no replacement activity. Moreover, the path of {status quo -(3) -(3) -(24) -(31)} would represent replacing defender B by challenger Y in year one, keeping the configuration for the second year and replacing defender A by challenger X in year three while keeping the configuration for the fourth year.

IX.5 Results and Discussion

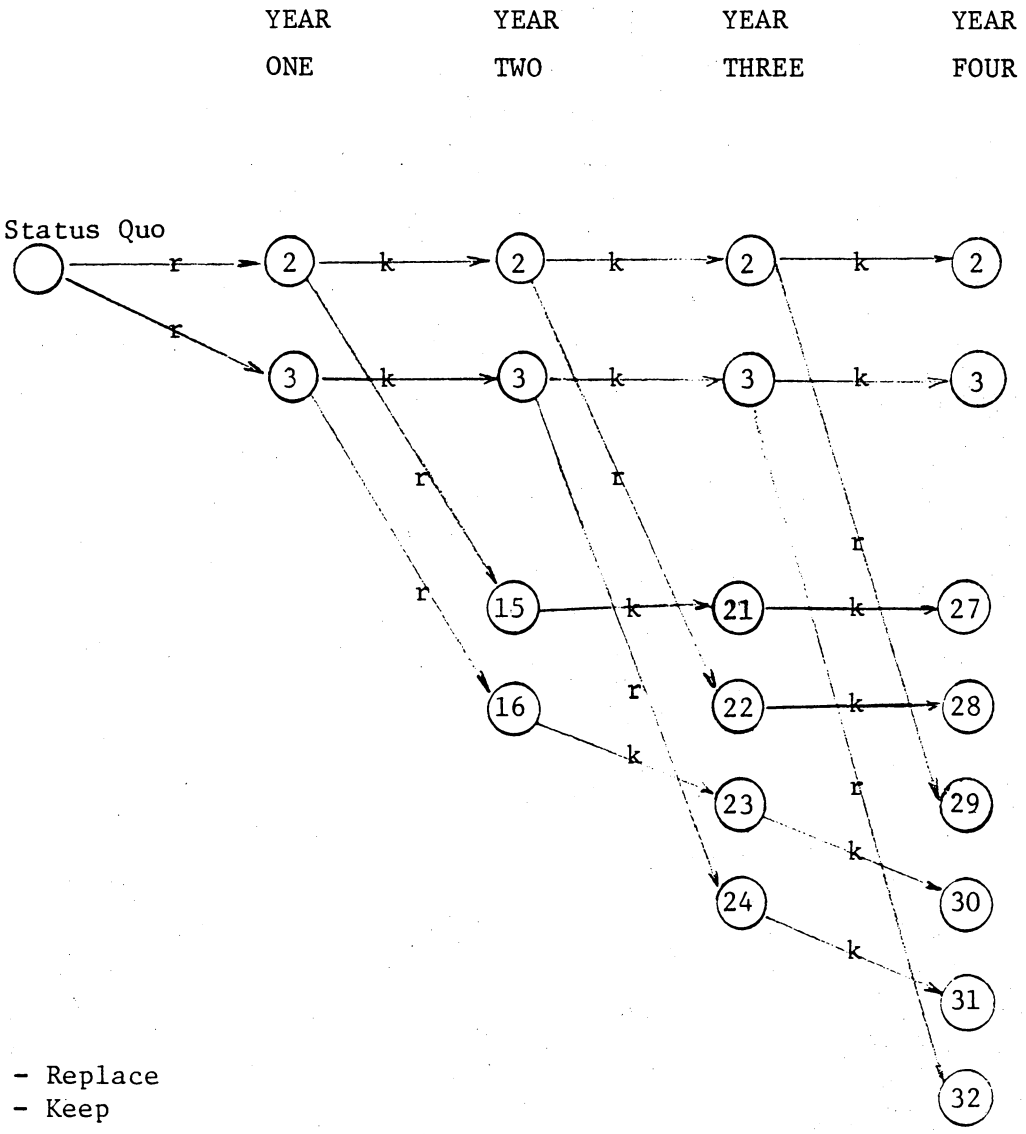
IX.5.1 The Optimal Replacement Sequence.

The maximum operating profit per FMS configuration for all configurations over the entire planning horizon are computed and the results are listed in Table IX.5. Then, the optimal return functions (f-values) are determined, the results are listed in Table IX.6. The maximum optimal value function at the end of the planning horizon is found to be $3,574,257 which belongs to configuration 31 of that year. This configuration consists of challenger machines 7 and 10, where machine 7 corresponds to machine Y made in year one while machine 10 corresponds to machine X made in year three. Tracing the FMS configurations sequence which lead to this maximum f-values, the resulting replacement policy is:

Table IX.4

Total Number of Configurations Per Year and Their Representations

YEAR ONE	YEAR TWO	YEAR THREE	YEAR FOUR
1- (2,3,4,5)	1- (2,3,4,5)	1- (2,3,4,5)	1- (2,3,4,5)
2- (6,3,4,5)	2- (6,3,4,5)	2- (6,3,4,5)	2- (6,3,4,5)
3- (7,3,4,5)	3- (7,3,4,5)	3- (7,3,4,5)	3- (7,3,4,5)
4- (2,6,4,5)	4- (8,3,4,5)	4- (8,3,4,5)	4- (8,3,4,5)
5- (2,7,4,5)	5- (9,3,4,5)	5- (9,3,4,5)	5- (9,3,4,5)
6- (6,4,5)	6- (2,6,4,5)	6-(10,3,4,5)	6-(10,3,4,5)
7- (7,4,5)	7- (2,7,4,5)	7-(11,3,4,5)	7-(11,3,4,5)
8- (6,7,4,5)	8- (2,8,4,5)	8- (2,6,4,5)	8-(12,3,4,5)
	9- (2,9,4,5)	9- (2,7,4,5)	9-(13,3,4,5)
	10- (6,4,5)	10- (2,8,4,5)	10- (2,6,4,5)
	11- (7,4,5)	11- (2,9,4,5)	11- (2,7,4,5)
	12- (8,4,5)	12-(2,10,4,5)	12- (2,8,4,5)
	13- (9,4,5)	13-(2,11,4,5)	13- (2,9,4,5)
	14- (6,7,4,5)	14- (6,4,5)	14-(2,10,4,5)
	15- (6,9,4,5)	15- (7,4,5)	15-(2,11,4,5)
	16- (7,8,4,5)	16- (8,4,5)	16-(2,12,4,5)
	17- (8,9,4,5)	17- (9,4,5)	17-(2,13,4,5)
		18- (10,4,5)	18- (6,4,5)
		19- (11,4,5)	19- (7,4,5)
		20- (6,7,4,5)	20- (8,4,5)
		21- (6,9,4,5)	21- (9,4,5)
		22-(6,11,4,5)	22- (10,4,5)
		23- (7,8,4,5)	23- (11,4,5)
		24-(7,10,4,5)	24- (12,4,5)
		25- (8,9,4,5)	25- (13,4,5)
		26-(8,11,4,5)	26- (6,7,4,5)
		27-(9,10,4,5)	27- (6,9,4,5)
		28-(10,11,4,5)	28-(6,11,4,5)
			29-(6,13,4,5)
			30- (7,8,4,5)
			31-(7,10,4,5)
			32-(7,12,4,5)
			33- (8,9,4,5)
			34-(8,11,4,5)
			35-(8,13,4,5)
			36-(9,10,4,5)
			37-(9,12,4,5)
			38-(10,11,4,5)
			39-(10,13,4,5)
			40-(11,12,4,5)
			41-(12,13,4,5)



r - Replace
k - Keep

Figure IX.4

A Sample of the Replacement Tree Showing Certain Configurations and Their Precedence Relationships.

Year	Configuration No.	Content	Optimal Return Value
1	5	(2,7,4,5)	\$707,226.0
2	7	(2,7,4,5)	\$1,490,185.0
3	24	(7,10,4,5)	\$2,483,559.0
4	41	(7,10,4,5)	\$3,574,257.0

That is, in the beginning of year one, machine B (machine 3) should be replaced by challenger Y (machine 7). This sytem configuration would be used for two years. Then, in the beginning of year three, replace machine A (machine 2) by challenger X (machine 10); this system configuration would be used till the end of the planning horizon.

IX.5.2 The Production Levels

The price-volume relationships corresponding to the system configurations in the replacement sequence are:

Year 1: Configuration (2,7,4,5)

Part Type	Price	Volume
1	160	3800
2	225	2200
3	300	3500

Table IX.5

Maximum Operating Profit Per Configuration
(Conf: Max Operating Profit)

```
    YEAR ONE

  1.  897094.00     2. 1095706.00     3. 1168156.00     4. 1216100.00     5. 1347462.00     6. 1035476.00
  7.       0.00     8. 1462960.00

    YEAR TWO

  1. 1036503.00     2. 1254185.00     3. 1347161.00     4. 1394582.00     5. 1455766.00     6. 1426504.00
  7. 1586948.00     8. 1541775.00     9. 1710914.00    10. 1069432.00    11.       0.00    12. 1381077.00
 13.       0.00    14. 1730523.00    15. 1838558.00    16. 1858669.00    17. 1942173.00

    YEAR THREE

  1. 1072734.00     2. 1342281.00     3. 1442998.00     4. 1506081.00     5. 1586560.00     6. 1679683.00
  7. 1716115.00     8. 1568041.00     9. 1760557.00    10. 1708458.00    11. 1897271.00    12. 1849399.00
 13. 2047607.00    14.       0.00    15.       0.00    16.       0.00    17.       0.00    18.       0.00
 19.       0.00    20. 1926368.00    21. 2062075.00    22. 2196752.00    23. 2082546.00    24. 2219486.00
 25.2182519.00    26. 2322351.00    27. 2341308.00    28. 2431486.00

    YEAR FOUR

  1. 1046169.00     2. 1360747.00     3. 1452330.00     4. 1551746.00     5. 1618226.00     6. 1750162.00
  7. 1780976.00     8. 1952567.00     9. 1940072.00    10. 1638941.00    11. 1852434.00    12. 1797052.00
 13. 2015143.00    14. 1962480.00    15. 2188294.00    16. 2139666.00    17. 2349063.00    18.       0.00
 19.       0.00    20.       0.00    21.       0.00    22.       0.00    23.       0.00    24.       0.00
 25.       0.00    26. 2048980.00    27. 2203235.00    28. 2375107.00    29. 2545223.00    30. 2235856.00
 31. 2395440.00    32. 2562917.00    33. 2359561.00    34. 2521080.00    35. 2688440.00    36. 2540089.00
 37. 2702554.00    38. 2665071.00    39. 2820915.00    40. 2854101.00    41. 2963591.00
```

Table IX.6

The Optimal Return Values (F-Values) for All Configurations:
(Conf. F-Value)

```
      YEAR ONE

  1. 480179.800       2. 545646.300       3. 570569.30        4. 643097.90        5. 707226.80        6. 572645.50
  7.-139754.60        8. 717381.00

      YEAR TWO

  1.  1018328.00      2.  1133091.00      3.  1190669.00      4.  1154077.00      5.  1167801.00      6.  1352582.00
  7.  1490185.00      8.  1260915.00      9.  1339952.00     10.  1101676.00     11.  -281324.40     12.  1199267.00
 13.   340425.10     14.  1504801.00     15.  1497694.00     16.  1573687.00     17.  1398975.00

      YEAR THREE

  1.  1539031.00      2.  1737365.00      3.  1831857.00      4.  1822866.00      5.  1857258.00      6.  1784111.00
  7.  1780856.00      8.  2094884.00      9.  2319890.00     10.  2054871.00     11.  2214160.00     12.  1891314.00
 13.  1977036.00     14.  1009276.00     15.  -392204.30     16.  1081292.00     17.   198855.20     18.   901865.80
 19.   878573.30     20.  2361022.00     21.  2397864.00     22.  2328640.00     23.  2490231.00     24.  2483559.00
 25.  2339814.00     26.  2280476.00     27.  2369638.00     28.  2099427.00

      YEAR FOUR

  1.  2114423.00      2.  2404925.00      3.  2533618.00      4.  2574685.00      5.  2625313.00      6.  2616927.00
  7.  2604318.00      8.  2484833.00      9.  2452551.00     10.  2915451.00     11.  3241708.00     12.  2941609.00
 13.  3200519.00     14.  2840904.00     15.  3024523.00     16.  2587737.00     17.  2677496.00     18.   928426.10
 19.  -489224.30     20.   979652.00     21.    76887.37     22.   772093.40     23.   722500.00     24.  1410922.00
 25.  1385512.00     26.  3310090.00     27.  3406824.00     28.  3398025.00     29.  3260387.00     30.  3521291.00
 31.  3574257.00     32.  3504364.00     33.  3413964.00     34.  3409355.00     35.  3278354.00     36.  3514946.00
 37.  3450487.00     38.  3279369.00     39.  3159525.00     40.  3262608.00     41.  2887378.00
```

Year 2: Configuration (2,7,4,5)

Part Type	Price	Volume
1	210	3800
2	275	2200
3	400	2700

Year 3: Configuration (7,10,4,5)

Part Type	Price	Volume
1	260	3800
2	325	2200
3	400	3500

Year 4: Configuration (7,10,4,5)

Part Type	Price	Volume
1	310	3800
2	400	1600
3	450	3500

In year one, versus the status quo configuration, the new configuration increases the production levels of both part type two and part type three from 1600 to 2200, and from 2700 to 3500, respectively. Note that in year two, the production level of part type three drops from 3500 to 2700. Apparently, the deterioration of machines had such an effect that it was no longer as profitable to produce at a higher output level. In the beginning of year three, once a new machine is acquired, the production level returns to its previous mark, 3500. However, after one year of deterioration, the production level of part type two is drops to 1600. In the next section, the assignment of machine parts are discussed.

IX.5.3 Machine Parts Assignment

The parts assignment corresponding to the system configurations in the optimal replacement sequence are shown in Tables IX.7, IX.8, IX.9, and IX.10. Note that the routings of part type one as well as type two remained the same for both years one and two; and in year three when machine 10 is acquired, the workload is shifted to the newer and more efficient equipment. In year four, while the routing of part type two remains identical to that of the preceding year, the production level is dropped to 1600.

For part type three, between years one and two, the production volume as well as the parts routing are changed. These changes can be attributed to the effect of deterioration. Naturally, when machines deteriorate, their production efficiency decline and hence a lower production output may be warranted. The change in routing of parts, however, is a relative issue. That is, if the older machines deteriorate faster, then a portion of what was previously assigned to the older machine would now be asigned to the less deteriorated equipment. In addition, even if the deterioration rates for both new and old machines are identical, their relative difference in absolute machining times could warrant the reassignment. Consider the following illustrative example: in year one for the first operation of part type

3 (variables 61 and 62 in Table IX.7), 788 parts are processed on machine 2 (in cell 2) while 2712 are processed on machine 7 (in cell 3). In year two, for the same operation (see Table IX.8), only 125 parts are assigned to machine 2 while 2575 are assigned to machine 7. In relative terms, in year one, machine 7 processes (2712 -788) = 1924 parts more than machine 2 whereas in year two, machine 7 exceeds machine 2 by (2575 -125) = 2450. The deterioration rates for both machines in these two years are identical 10%. Apparently, the relative workload shift came from the relative difference in absolute machine times. Similar situations can be found in years 3 and 4.

As can be observed, the bulk of the workload is generally assigned to the newer equipment. For the first two years, machine 7 is assigned the heaviest workload while in the last two years, machine 10 is assigned the most workload.

IX.5.4 Summary

In the beginning of the planning horizon, machine B is replaced by machine Y. That is, the joint return from disposing of an inefficient machine and acquiring a new equipment exceeds the cost of replacement. On the other hand, although machine A is less efficient than challenger X, the production environment (deterioration and obsolescence, price-volume relationship, routing, capitalized cost, etc.) does not find replacing machine A by challenger X in the first two years as desirable. Tn the beginning of year three, however, as machine two deteriorates and at the same time machine X becomes more efficient

Table IX.7

Optimal Parts Assignment for FMS Configuration (2,7,4,5) - in Year One

THE OPTIMUM IS
:347462.00

THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

VAR	P	K	M	S	OBJ. COEFF.	Y(P,K,M,S)
1	1	1	2	1	20.94	3799.98
2	1	2	3	2	15.75	0.0
3	1	2	4	2	16.50	3799.99
4	1	3	4	3	17.47	0.00
5	1	3	4	4	6.80	3799.99
6	1	3	5	3	16.65	0.0
7	1	3	5	4	21.98	0.0
8	1	4	2	4	21.12	0.0
9	1	4	2	5	23.79	0.0
10	1	4	3	4	10.87	3799.99
11	1	4	3	5	13.53	0.0
12	1	4	5	4	30.62	0.0
13	1	4	5	5	17.29	0.00
14	1	5	3	2	17.48	0.0
15	1	5	3	3	4.15	3799.99
16	1	5	3	5	12.15	0.0
17	1	5	4	2	20.75	0.0
18	1	5	4	3	23.42	0.0
19	1	5	4	5	15.42	0.0
20	1	5	5	2	16.75	0.00
21	1	5	5	3	19.41	0.0
22	1	5	5	5	11.41	0.00
23	1	6	1	3	5.33	3799.99
24	1	6	1	4	10.67	0.00
25	1	6	1	5	13.33	0.00
26	1	6	1	1	-160.00	3800.00
27	2	1	3	1	20.10	2199.99
28	2	2	2	3	21.20	2200.00
29	2	2	3	3	12.10	0.0
30	2	3	2	2	8.38	2199.99
31	2	3	2	3	11.04	0.0
32	2	3	3	2	18.52	0.0
33	2	3	3	3	5.19	0.00
34	2	3	4	2	20.75	0.0
35	2	3	4	3	23.42	0.0
36	2	4	3	2	25.44	0.00
37	2	4	3	3	12.10	0.00
38	2	4	3	4	17.44	0.00
39	2	4	4	2	42.00	0.0
40	2	4	4	3	44.67	0.0
41	2	4	4	4	34.00	0.0
42	2	4	5	2	30.79	2200.00
43	2	4	5	3	33.45	0.0
44	2	4	5	4	38.79	0.0
45	2	5	4	3	40.42	0.0
46	2	5	4	4	29.75	0.00
47	2	5	4	5	32.42	0.01
48	2	5	5	3	34.56	0.0
49	2	5	5	4	39.89	0.0
50	2	5	5	5	26.56	2199.99
51	2	6	2	4	16.10	0.0
52	2	6	2	5	18.76	2199.99
53	2	6	3	4	10.52	0.0
54	2	6	3	5	13.19	0.0
55	2	6	5	4	23.71	0.0
56	2	6	5	5	10.37	0.0
57	2	7	1	2	2.67	2199.99
58	2	7	1	3	5.33	0.00
59	2	7	1	5	13.33	0.00
60	2	7	1	1	-225.00	2200.00
61	3	1	2	1	30.93	787.98
62	3	1	3	1	16.65	2711.99
63	3	2	2	2	17.87	787.98
64	3	2	2	3	20.53	0.0
65	3	2	3	2	21.98	0.0
66	3	2	3	3	8.65	2711.99
67	3	2	4	2	42.00	0.0
68	3	2	4	3	44.67	0.0
69	3	2	5	2	29.40	0.0
70	3	2	5	3	32.07	0.0
71	3	3	3	2	16.79	787.98
72	3	3	3	3	3.46	2711.99
73	3	3	3	4	8.79	0.00
74	3	3	3	5	11.46	0.00
75	3	3	4	2	20.75	0.0
76	3	3	4	3	23.42	0.0
77	3	3	4	4	12.75	0.0
78	3	3	4	5	15.42	0.0
79	3	4	2	3	8.25	0.0
80	3	4	2	4	13.58	0.0
81	3	4	3	3	2.77	3499.98
82	3	4	3	4	8.10	0.00
83	3	5	3	2	20.25	0.0
84	3	5	3	3	6.92	3499.98
85	3	5	5	2	22.62	0.00

Table IX.7 (cont'd)

86	3	5	5	3	25.29	0.0
87	3	6	3	3	2.77	3499.98
88	3	6	3	5	10.77	0.0
89	3	6	4	3	19.17	0.0
90	3	6	4	5	11.17	0.0
91	3	6	5	3	14.50	0.0
92	3	6	5	5	6.50	0.00
93	3	7	2	3	13.83	3499.99
94	3	7	2	4	19.17	0.00
95	3	7	2	5	21.83	0.00
96	3	8	2	2	10.05	3499.99
97	3	8	4	2	22.45	0.0
98	3	9	2	2	3.24	3499.99
99	3	9	2	4	11.24	0.00
100	3	10	1	2	2.67	3499.99
101	3	10	1	1	-300.00	3500.00

Table IX.8

Optimal Parts Assignment for FMS Configuration (2,7,4,5) - in Year Two

```
                THE OPTIMUM IS
                  1586948.00


     THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :


  VAR    P    K    M    S        OBJ.     Y(P,K,M,S)
                                 COEFF.

    1    1    1    2    1        25.04     3799.98
    2    1    2    3    2        17.80        0.0
    3    1    2    4    2        19.78     3799.99
    4    1    3    4    3        20.52        0.00
    5    1    3    4    4         8.79     3799.99
    6    1    3    5    3        20.00        0.0
    7    1    3    5    4        25.87        0.0
    8    1    4    2    4        25.80        0.0
    9    1    4    2    5        28.73        0.0
   10    1    4    3    4        13.03     3799.99
   11    1    4    3    5        15.96        0.0
   12    1    4    5    4        37.07        0.0
   13    1    4    5    5        22.40        0.00
   14    1    5    3    2        20.04        0.0
   15    1    5    3    3         5.37     3799.99
   16    1    5    3    5        14.17        0.0
   17    1    5    4    2        25.27        0.0
   18    1    5    4    3        28.21        0.0
   19    1    5    4    5        19.41        0.0
   20    1    5    5    2        20.65        0.00
   21    1    5    5    3        23.58        0.0
   22    1    5    5    5        14.78        0.00
   23    1    6    1    3         5.87     3799.99
   24    1    6    1    4        11.73        0.00
   25    1    6    1    5        14.67        0.00
   26    1    6    1    1      -210.00     3800.00
   27    2    1    3    1        24.46     2199.99
   28    2    2    2    3        26.95     2199.99
   29    2    2    3    3        15.66        0.0
   30    2    3    2    2        10.85     2199.99
   31    2    3    2    3        13.78        0.00
   32    2    3    3    2        21.38        0.0
   33    2    3    3    3         6.71        0.0
   34    2    3    4    2        25.27        0.0
   35    2    3    4    3        28.21        0.0
   36    2    4    3    2        30.33        0.0
   37    2    4    3    3        15.66        0.0
   38    2    4    3    4        21.53        0.0
   39    2    4    4    2        52.73        0.0
   40    2    4    4    3        55.67        0.0
   41    2    4    4    4        43.93        0.00
   42    2    4    5    2        38.84     2199.99
   43    2    4    5    3        41.77        0.00
   44    2    4    5    4        47.64        0.0
   45    2    5    4    3        50.17        0.0
   46    2    5    4    4        38.44        0.00
   47    2    5    4    5        41.37        0.0
   48    2    5    5    3        43.20        0.00
   49    2    5    5    4        49.07        0.0
   50    2    5    5    5        34.40     2199.99
   51    2    6    2    4        19.29        0.00
   52    2    6    2    5        22.22     2199.99
   53    2    6    3    4        12.58        0.0
   54    2    6    3    5        15.51        0.0
   55    2    6    5    4        28.11        0.0
   56    2    6    5    5        13.44        0.0
   57    2    7    1    2         2.93     2199.99
   58    2    7    1    3         5.87        0.00
   59    2    7    1    5        14.67        0.00
   60    2    7    1    1      -275.00     2200.00
   61    3    1    2    1        37.99      124.70
   62    3    1    3    1        19.99     2575.27
   63    3    2    2    2        23.14      124.71
   64    3    2    2    3        26.08        0.0
   65    3    2    3    2        25.85        0.0
   66    3    2    3    3        11.19     2575.27
   67    3    2    4    2        52.73        0.0
   68    3    2    4    3        55.67        0.0
   69    3    2    5    2        37.05        0.0
   70    3    2    5    3        39.98        0.0
   71    3    3    3    2        19.14      124.70
   72    3    3    3    3         4.47     2575.27
   73    3    3    3    4        10.34        0.00
   74    3    3    3    5        13.27        0.00
   75    3    3    4    2        25.27        0.0
   76    3    3    4    3        28.21        0.0
   77    3    3    4    4        16.47        0.0
   78    3    3    4    5        19.41        0.0
   79    3    4    2    3        10.17        0.00
   80    3    4    2    4        16.03        0.0
   81    3    4    3    3         3.58     2699.98
   82    3    4    3    4         9.45        0.00
   83    3    5    3    2        23.62        0.0
   84    3    5    3    3         8.95     2699.98
```

Table IX.8 (cont'd)

85	3	5	5	2	28.27	0.0
86	3	5	5	3	31.20	0.0
87	3	6	3	3	3.58	2699.99
88	3	6	3	5	12.38	0.0
89	3	6	4	3	22.72	0.0
90	3	6	4	5	13.92	0.0
91	3	6	5	3	17.22	0.0
92	3	6	5	5	8.42	0.00
93	3	7	2	3	17.40	2699.99
94	3	7	2	4	23.27	0.00
95	3	7	2	5	26.20	0.00
96	3	8	2	2	13.02	2699.99
97	3	8	4	2	27.47	0.0
98	3	9	2	2	4.20	2699.99
99	3	9	2	4	13.00	-0.00
100	3	10	1	2	2.93	2699.99
101	3	10	1	1	-400.00	2700.00

Table IX.9

Optimal Parts Assignment for FMS Configuration (7,10,4,5) - In Year Three

```
              THE OPTIMUM IS
                2219486.00


     THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :

VAR     P      K      M      S       OBJ.      Y(P,K,M,S)
                                     COEFF.

  1     1      1      3      1      15.12      3799.98
  2     1      2      2      3       7.28         0.0
  3     1      2      3      3       4.35      3799.99
  4     1      2      4      3      27.10         0.0
  5     1      3      3      2      20.48         0.0
  6     1      3      3      3       4.35      3799.99
  7     1      3      3      4      10.80         0.0
  8     1      3      4      2      21.03         0.00
  9     1      3      4      3      24.26         0.0
 10     1      3      4      4      11.35         0.00
 11     1      3      5      2      20.96         0.00
 12     1      3      5      3      24.19         0.0
 13     1      3      5      4      30.64         0.0
 14     1      4      2      3      12.49      3799.99
 15     1      4      2      4      18.95         0.00
 16     1      4      2      5      22.17         0.0
 17     1      4      5      3      38.70         0.0
 18     1      4      5      4      45.15         0.0
 19     1      4      5      5      29.02         0.0
 20     1      5      2      2       6.95      3799.99
 21     1      5      2      5      19.86         0.00
 22     1      5      3      2      22.22         0.0
 23     1      5      3      5      15.77         0.0
 24     1      5      4      2      30.97         0.0
 25     1      5      4      5      24.52         0.0
 26     1      5      5      2      25.60         0.0
 27     1      5      5      5      19.15         0.0
 28     1      6      1      2       3.23      3799.99
 29     1      6      1      3       6.45         0.00
 30     1      6      1      4      12.91         0.00
 31     1      6      1      5      16.13         0.00
 32     1      6      1      1    -260.00      3800.00
 33     2      1      2      1      33.17         0.00
 34     2      1      3      1      27.08      2199.99
 35     2      2      2      2      20.27         0.00
 36     2      2      2      3      23.49         0.0
 37     2      2      3      2      29.19         0.0
 38     2      2      3      3      13.05      2199.99
 39     2      3      2      2       8.69         0.0
 40     2      3      2      3      11.91         2.40
 41     2      3      4      2      30.97         0.0
 42     2      3      4      3      34.20      2197.60
 43     2      4      2      2      20.27         0.00
 44     2      4      2      4      29.95         0.0
 45     2      4      3      2      29.19         0.0
 46     2      4      3      4      19.51      2197.60
 47     2      4      4      2      66.45         0.0
 48     2      4      4      4      56.77         0.0
 49     2      4      5      2      49.17         2.40
 50     2      4      5      4      58.85         0.0
 51     2      5      3      2      29.19         0.0
 52     2      5      3      3      13.05      2197.60
 53     2      5      3      4      19.51         0.00
 54     2      5      3      5      22.73         0.0
 55     2      5      4      2      59.36         0.0
 56     2      5      4      3      62.58         0.0
 57     2      5      4      4      49.68         0.0
 58     2      5      4      5      52.90         0.0
 59     2      5      5      2      51.02         0.0
 60     2      5      5      3      54.25         0.0
 61     2      5      5      4      60.70         0.0
 62     2      5      5      5      44.57         2.40
 63     2      6      2      3      11.91      2197.60
 64     2      6      2      4      18.37         0.00
 65     2      6      2      5      21.59         0.0
 66     2      6      5      3      27.09         0.0
 67     2      6      5      4      33.54         0.0
 68     2      6      5      5      17.41         2.40
 69     2      7      1      2       3.23      2197.60
 70     2      7      1      5      16.13         2.40
 71     2      7      1      1    -325.00      2200.00
 72     3      1      2      1      27.38      3499.99
 73     3      1      3      1      22.73         0.0
 74     3      2      2      2      14.48      3499.99
 75     3      2      2      3      17.70         0.00
 76     3      2      3      2      29.19         0.0
 77     3      2      3      3      13.05         0.0
 78     3      2      4      2      66.45         0.0
 79     3      2      4      3      69.68         0.0
 80     3      2      5      2      46.84         0.0
 81     3      2      5      3      50.07         0.0
 82     3      3      2      2       5.79      3499.99
 83     3      3      2      3       9.02         0.0
 84     3      3      2      4      15.47         0.0
```

Table IX.9 (cont'd)

85	3	3	2	5	18.70	0.0
86	3	3	3	2	20.48	0.0
87	3	3	3	3	4.35	0.00
88	3	3	3	4	10.80	0.00
89	3	3	3	5	14.03	0.00
90	3	3	4	2	30.97	0.0
91	3	3	4	3	34.20	0.0
92	3	3	4	4	21.29	0.0
93	3	3	4	5	24.52	0.0
94	3	4	2	2	4.63	3499.99
95	3	4	2	3	7.86	0.0
96	3	4	2	4	14.31	0.0
97	3	4	3	2	22.66	0.0
98	3	4	3	3	6.53	0.00
99	3	4	3	4	12.98	0.00
100	3	5	2	2	11.58	964.72
101	3	5	2	3	14.81	0.0
102	3	5	3	2	27.01	0.0
103	3	5	3	3	10.88	0.00
104	3	5	5	2	35.47	2535.28
105	3	5	5	3	38.70	0.0
106	3	6	2	2	4.63	0.01
107	3	6	2	3	7.86	0.0
108	3	6	2	5	17.54	0.0
109	3	6	3	2	19.61	0.0
110	3	6	3	3	3.48	0.00
111	3	6	3	5	13.16	0.0
112	3	6	4	2	23.87	0.0
113	3	6	4	3	27.10	0.0
114	3	6	4	5	17.42	0.0
115	3	6	5	2	17.36	964.72
116	3	6	5	3	20.59	0.0
117	3	6	5	5	10.91	2535.26
118	3	7	3	2	22.66	0.0
119	3	7	3	3	6.53	0.00
120	3	7	3	4	12.98	0.00
121	3	7	3	5	16.21	3499.99
122	3	8	3	3	6.53	3499.99
123	3	8	4	3	37.03	0.0
124	3	9	3	3	2.18	3499.99
125	3	9	3	4	8.63	0.00
126	3	10	1	3	6.45	3499.99
127	3	10	1	1	-400.00	3500.00

Table IX.10

Optimal Parts Assignment for FMS Configuration (7,10,4,5) - In Year Four

```
                 THE OPTIMUM IS
                   2395440.00


      THE ASSIGNMENTS OF PARTS ARE AS FOLLOW :


VAR    P    K    M    S       OBJ.     Y(P,K,M,S)
                              COEFF.

  1    1    1    3    1      17.69     3799.99
  2    1    2    2    3       8.80        0.0
  3    1    2    3    3       5.63     3800.00
  4    1    2    4    3      32.54        0.0
  5    1    3    3    2      23.38        0.0
  6    1    3    3    3       5.63     3800.00
  7    1    3    3    4      12.73        0.0
  8    1    3    4    2      25.32        0.00
  9    1    3    4    3      28.87        0.0
 10    1    3    4    4      14.67        0.00
 11    1    3    5    2      25.89        0.0
 12    1    3    5    3      29.44        0.0
 13    1    3    5    4      36.54        0.0
 14    1    4    2    3      15.54     3799.99
 15    1    4    2    4      22.64        0.00
 16    1    4    2    5      26.19        0.00
 17    1    4    5    3      48.24        0.0
 18    1    4    5    4      55.34        0.0
 19    1    4    5    5      37.59        0.0
 20    1    5    2    2       8.99     3799.99
 21    1    5    2    5      23.19        0.00
 22    1    5    3    2      25.63        0.0
 23    1    5    3    5      18.53        0.0
 24    1    5    4    2      38.16        0.0
 25    1    5    4    5      31.06        0.0
 26    1    5    5    2      31.91        0.0
 27    1    5    5    5      24.81        0.0
 28    1    6    1    2       3.55     3800.00
 29    1    6    1    3       7.10        0.00
 30    1    6    1    4      14.20        0.00
 31    1    6    1    5      17.75        0.00
 32    1    6    1    1    -310.00     3800.00
 33    2    1    2    1      40.43        0.00
 34    2    1    3    1      33.18     1600.00
 35    2    2    2    2      26.23        0.00
 36    2    2    2    3      29.78        0.0
 37    2    2    3    2      34.64        0.0
 38    2    2    3    3      16.90     1600.00
 39    2    3    2    2      11.24        0.0
 40    2    3    2    3      14.79        0.01
 41    2    3    4    2      38.16        0.0
 42    2    3    4    3      41.71     1599.99
 43    2    4    2    2      26.23        0.00
 44    2    4    2    4      36.88        0.0
 45    2    4    3    2      34.64        0.0
 46    2    4    3    4      24.00     1600.00
 47    2    4    4    2      84.01        0.0
 48    2    4    4    4      73.37        0.0
 49    2    4    5    2      62.43        0.01
 50    2    4    5    4      73.08        0.0
 51    2    5    3    2      34.64        0.0
 52    2    5    3    3      16.90     1599.99
 53    2    5    3    4      24.00        0.00
 54    2    5    3    5      27.55        0.0
 55    2    5    4    2      74.84        0.0
 56    2    5    4    3      78.39        0.0
 57    2    5    4    4      64.20        0.0
 58    2    5    4    5      67.75        0.0
 59    2    5    5    2      64.84        0.0
 60    2    5    5    3      68.39        0.0
 61    2    5    5    4      75.49        0.0
 62    2    5    5    5      57.74        0.00
 63    2    6    2    3      14.79     1599.99
 64    2    6    2    4      21.89        0.00
 65    2    6    2    5      25.44        0.0
 66    2    6    5    3      33.20        0.0
 67    2    6    5    4      40.30        0.0
 68    2    6    5    5      22.55        0.00
 69    2    7    1    2       3.55     1599.99
 70    2    7    1    5      17.75        0.01
 71    2    7    1    1    -400.00     1600.00
 72    3    1    2    1      32.93     3385.73
 73    3    1    3    1      27.55      114.26
 74    3    2    2    2      18.74     3385.73
 75    3    2    2    3      22.29        0.0
 76    3    2    3    2      34.64        0.0
 77    3    2    3    3      16.90      114.26
 78    3    2    4    2      84.01        0.0
 79    3    2    4    3      87.56        0.0
 80    3    2    5    2      59.43        0.0
 81    3    2    5    3      62.98        0.0
 82    3    3    2    2       7.49     3385.73
 83    3    3    2    3      11.04        0.0
 84    3    3    2    4      18.14        0.0
```

Table IX.10 (cont'd)

85	3	3	2	5	21.69	0.0
86	3	3	3	2	23.38	0.0
87	3	3	3	3	5.63	114.26
88	3	3	3	4	12.73	0.00
89	3	3	3	5	16.28	0.00
90	3	3	4	2	38.16	0.0
91	3	3	4	3	41.71	0.0
92	3	3	4	4	27.51	0.0
93	3	3	4	5	31.06	0.0
94	3	4	2	2	6.00	3385.73
95	3	4	2	3	9.54	0.0
96	3	4	2	4	16.64	0.0
97	3	4	3	2	26.20	0.0
98	3	4	3	3	8.45	114.26
99	3	4	3	4	15.55	0.00
100	3	5	2	2	14.99	0.00
101	3	5	2	3	18.54	0.0
102	3	5	3	2	31.83	0.0
103	3	5	3	3	14.08	114.26
104	3	5	5	2	44.69	3385.74
105	3	5	5	3	48.24	0.0
106	3	6	2	2	6.00	0.00
107	3	6	2	3	9.54	0.0
108	3	6	2	5	20.19	0.0
109	3	6	3	2	22.25	0.0
110	3	6	3	3	4.51	114.26
111	3	6	3	5	15.15	2002.99
112	3	6	4	2	28.99	0.0
113	3	6	4	3	32.54	0.0
114	3	6	4	5	21.89	0.0
115	3	6	5	2	21.23	0.0
116	3	6	5	3	24.78	0.0
117	3	6	5	5	14.13	1382.75
118	3	7	3	2	26.20	0.0
119	3	7	3	3	8.45	2117.24
120	3	7	3	4	15.55	0.00
121	3	7	3	5	19.10	1382.75
122	3	8	3	3	8.45	3499.99
123	3	8	4	3	45.38	0.0
124	3	9	3	3	2.82	3499.99
125	3	9	3	4	9.91	0.00
126	3	10	1	3	7.10	3499.99
127	3	10	1	1	-450.00	3500.00

through technological improvement, the difference is found to merit replacing defender A by challenger X.

IX.6 SOME PARAMETRIC ANALYSIS

IX.6.1 Time-value of Money

The time-value-of-money used for the preceding analysis is 10%. To see how the optimal replacement sequence changes with respect to different values of the time-value-of-money, the preceding problem is solved using a rate ranging from 0 to 100%. The results are shown in Table IX.11 and plotted in Figure IX.5.

Between 0-25%, the sequence {(2,7,4,5), (2,7,4,5), (7,10,4,5); (7,10,4,5)} is recommended. This implies that it does not matter how inexpensive the opportunity cost is, acquisition of both machine Y in year one and machine X in year three remains the optimal replacement strategy. As the interest rate goes up to 26%, the cost of replacement becomes significant enough that the acquisition of machine X is delayed by one year. When the interest rate hits the 46% mark, the replacement cost reaches the point that it is no longer desirable to replace machine 2. Similarly, as the interest rate increases, replacement alternatives are inhibited. In fact, when the rate reaches 75%, no replacement is recommended.

IX.6.2 Different Deterioration Rates

Instead of having a 10% deterioration rate for defender A, challenger X and challenger Y, in 5% deterioration rate B used. For these deterioration rates, the optimal replacement sequence remains unchanged. Table IX.12 lists the F-values for all configurations as well as the optimal sequence. The price-volume combinations for configurations in the optimal replacement sequence are:

	Year One	Year Two	Year Three	Year Four
Part One:	160 - 3800	210 - 3800	260 - 3800	310 - 3800
Part Two:	225 - 2200	275 - 2200	300 - 3000	350 - 3000
Part Three:	300 - 3500	350 - 3500	400 - 3500	450 - 3500

As can be observed, other than increasing the production level of part type two in year three from 2200 to 3000, the production levels for all part types within the planning horizon remained the same.

IX.6.3 A 10% Obsolescence Rate for Both Challengers

Instead of a 5% obsolescence rate, a 10% rate is used for both challengers X and Y. The resulting optimal return values are listed in Table IX.13. The optimal replacement sequence remains the same, indicating that the faster obsolescence rate does not alter either replacement candidates or the replacement frequency. The price-volume combinations for each part type for each year are:

Table IX.11

Effects of Time-Value-of-Money on Replacement Policy

TIME-VALUE-OF-MONEY (PERCENTAGE)	OPTIMAL REPLACEMENT SEQUENCE	F-VALUES
0	(2,7,4,5/2,7,4,5/7,10,4,5/7,10,4,5)	3,380,593
4		3,465,093
6		3,503,937
8		3,540,366
10		3,574,257
12		3,605,501
14	''	3,633,969
16		3,659,547
18		3,682,099
20		3,710,506
22		3,717,628
24		3,730,337
26	(2,7,4,5/2,7,4,5/2,7,4,5/7,12,4,5)	3,742,440
28		3,758,491
30		3,771,030
36	''	3,786,146
40		3,775,942
44		3,748,142
46	(2,7,4,5/2,7,4,5/2,7,4,5/2,7,4,5)	3,728,215
48		3,722,018
50		3,711,363
52		3,695,772
54	''	3,675,375
56		3,649,888
58		3,619,136
60		3,582,922
62	(2,3,4,5/2,3,4,5/2,9,4,5/2,9,4,5)	3,554,813
66		3,497,819
68	''	3,463,430
70	(2,3,4,5/2,3,4,5/2,11,4,5/2,11,4,5)	3,434,194
72	''	3,412,550
74		3,387,864
76	(2,3,4,5/2,3,4,5/2,3,4,5/2,3,4,5)	3,390,864
80		3,418,341
90	''	3,444,192
100		3,399,685

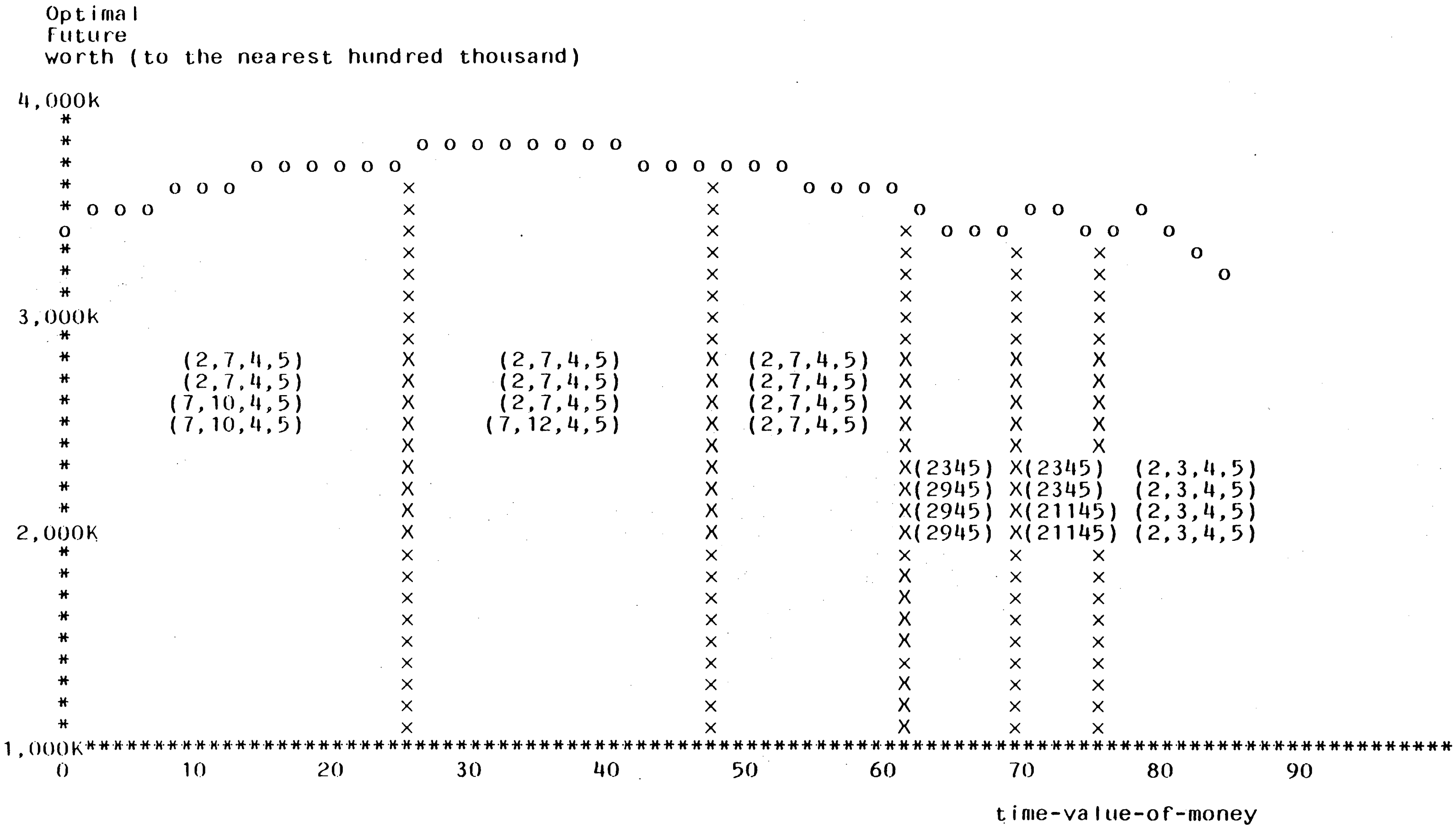


Figure IX.5

Plot of Optimal future Worth Against Time-Value-Of-Money
also Shwoing Regions of Optimal Replacement Sequence

Table IX.12

5% Deterioration Rate for Defender A, Challenger X and Challenger Y. The Optimal Return Values (F-Values) for all Configurations: (Conf. F-Value)

```
   YEAR ONE

 1. 480180.000    2. 545646.000    3. 570568.875    4. 643097.500    5. 707226.312    6. 572645.437    7.-139754.625
 8. 717380.500


   YEAR TWO

 1. 1065876.00    2. 1186344.00    3. 1228663.00    4. 1177395.00    5. 1186235.00    6. 1405642.00    7. 1544783.00
 8. 1288289.00    9. 1366748.00   10. 1196168.00   11.-281324.375   12. 1217411.00   13. 340425.250   14. 1549463.00
15. 1522996.00   16. 1597506.00   17. 1401372.00


   YEAR THREE

 1. 1707750.00    2. 1908380.00    3. 1961014.00    4. 1932603.00    5. 1937215.00    6. 1884110.00    7. 1866055.00
 8. 2274325.00    9. 2491758.00   10. 2178396.00   11. 2337700.00   12. 2012854.00   13. 2096496.00   14. 1103768.00
15. -392204.312  16. 1099436.00   17. 198855.375   18. 949413.562   19. 926121.125   20. 2512171.00   21. 2502027.00
22. 2435727.00   23. 2599893.00   24. 2594230.00   25. 2399485.00   26. 2332979.00   27. 2426486.00   28. 2158707.00


   YEAR FOUR

 1. 2456594.00    2. 2779004.00    3. 2823654.00    4. 2851752.00    5. 2833477.00    6. 2844180.00    7. 2786432.00
 8. 2743551.00    9. 2688282.00   10. 3298093.00   11. 3630064.00   12. 3256081.00   13. 3511347.00   14. 3124300.00
15. 3300385.00   16. 2878701.00   17. 2975816.00   18. 1022918.06   19.-489224.250   20. 997796.062   21. 76887.5000
22. 819641.187   23. 770047.750   24. 1579641.00   25. 1554231.00   26. 3657466.00   27. 3674763.00   28. 3629788.00
29. 3529202.00   30. 3805779.00   31. 3822770.00   32. 3775955.00   33. 3602287.00   34. 3556382.00   35. 3463112.00
36. 3676927.00   37. 3642786.00   38. 3406577.00   39. 3321835.00   40. 3415830.00   41. 3068648.00



      THE OPTIMAL FMS SEQUENCE IS AS FOLLOW:


                     YEAR         CONF.        F-VALUES
                      1             5           707226.31
                      2             7          1544783.00
                      3            24          2594230.00
                      4            31          3822770.00
```

	Year One	Year Two	Year Three	Year Four
Part One:	160 - 3800	210 - 3800	260 - 3800	310 - 3800
Part Two:	225 - 2200	275 - 2200	325 - 2200	400 - 1600
Part Three:	300 - 3500	400 - 2700	400 - 3500	400 - 3500

It appears also that the 10% obsolescence rate does not alter the production levels from the previous 5% case.

IX.6.4 Change in Selling Prices

In the previous illustrative example, the selling price of each part type was assumed to increase by $50 per year. Here, instead of having a fixed amount increase annually, an annual 10 percentage raise in selling price is used. That is, the selling prices of each part type at corresponding price breaks are described as follows:

	Part Type One:			Part Type Two:			Part Type Three:		
	Price-breaks			Price-breaks			Price-breaks		
Year 1	200	180	160	250	225	200	400	350	300
Year 2	220	198	176	275	247.5	2200	400	385	330
Year 3	242	217.8	193.6	302.5	272	242	484	424	363
Year 4	260.2	239.6	213	333	300	266	532	466	399

The F-values as well as the optimal replacement sequence for this demand profile is listed in Table IX.14. Again, the optimal replacement

Table IX.13

A 10% Obsolescence Rate for the Entire Planning Horizon
The Optimal Return Values (F-Values) for all Configurations: (Conf. F-Value)

```
  YEAR ONE

 1. 480180.000    2. 545646.000    3. 570568.875    4. 643097.500    5. 707226.312    6. 572645.437    7.-139754.625
 8. 717380.500

  YEAR TWO

 1. 1018328.37    2. 1133090.00    3. 1190669.00    4. 1186194.00    5. 1167801.00    6. 1352582.00    7. 1490184.00
 8. 1287148.00    9. 1339952.00   10. 1101675.00   11.-281324.375   12. 1225587.00   13. 340425.250   14. 1504800.00
15. 1497693.00   16. 1599132.00   17. 1420071.00

  YEAR THREE

 1. 1539031.00    2. 1737364.00    3. 1831857.00    4. 1887954.00    5. 1857258.00    6. 1859660.00    7. 1780856.00
 8. 2094884.00    9. 2319889.00   10. 2109064.00   11. 2214160.00   12. 1953173.00   13. 1977036.00   14. 1009275.06
15. -392204.312  16.  1107612.00  17.  198855.375  18.  901865.937  19.  878573.500  20.  2361021.00  21.  2397863.00
22. 2328640.00   23. 2542715.00   24. 2541674.00   25. 2387995.00   26. 2330377.00   27. 2425819.00   28. 2151449.00

  YEAR FOUR

 1. 2114423.00    2. 2404924.00    3. 2533618.00    4. 2679124.00    5. 2625313.00    6. 2771407.00    7. 2604318.00
 8. 2618600.00    9. 2452551.00   10. 2915451.00   11. 3241707.00   12. 3028464.00   13. 3200519.00   14. 2973938.00
15. 3024523.00   16. 2703633.00   17. 2677496.00   18. 928425.125   19.-489224.250   20. 1005972.06   21. 76887.5000
22. 772093.562   23. 722500.125   24. 1410922.00   25. 1385512.00   26. 3310089.00   27. 3406823.00   28. 3398025.00
29. 3260387.00   30. 3605610.00   31. 3699689.00   32. 3613436.00   33. 3494665.00   34. 3487105.00   35. 3360398.00
36. 3637147.00   37. 3553085.00   38. 3390647.00   39. 3277079.00   40. 3360490.00   41. 2965643.00


    THE OPTIMAL FMS SEQUENCE IS AS FOLLOW:


                   YEAR          CONF.        F-VALUES
                     1             5           707226.31
                     2             7          1490184.00
                     3            24          2541674.00
                     4            31          3699689.00
```

sequence remains unchanged. The price-volume combinations for respective part types over the entire planning horizon are as follows:

	Year One	Year Two	Year Three	Year Four
Part One:	160 - 3800	176 - 3800	193.6 - 3800	213 - 3800
Part Two:	225 - 2200	275 - 1600	272.3 - 2200	333 - 1600
Part Three:	300 - 3500	385 - 2700	423.5 - 2700	466 - 2700

The production level of part type one remains constant throughout the entire planning horizon. That of part type two first drops from 2200 to 1600 in year two; raises back to 2200 and in year four, drops back to 1600. For part type three, its production drops from 3500 to 2700 and thereafter stays at this level.

IX.6.5 Annual Increase in Unit Cost of Input

Instead of having a 6% annual increase in the unit cost of indirect labor, assume that the rate of increase is 16%. Table IX.15 lists the results of this new rate. There is no change in the optimal replacement sequence. The price-volume combinations for the optimal replacement sequence are:

	Year One	Year Two	Year Three	Year Four
Part One:	160 - 3800	210 - 3800	260 - 3800	310 - 3800
Part Two:	225 - 2200	275 - 2200	350 - 1600	400 - 1600
Part Three:	300 - 3500	400 - 2700	400 - 3500	500 - 2700

Table IX.14

A 10% Annual Increase in Selling Price for All Part Types
The Optimal REturn Values (F-Values) for all Configurations: (Conf. F-Value)

```
  YEAR ONE

 1. 480180.000     2. 545646.000     3. 570568.875     4. 643097.500     5. 707226.312     6. 572645.437     7. -139754.625
 8. 717380.500

  YEAR TWO

 1. 891460.125     2. 1012972.00     3. 1063800.00     4. 1031441.81     5. 1040913.06     6. 1220158.00     7.  1352506.00
 8. 1127141.00     9. 1187016.00    10. 1039966.25    11.-281324.375    12. 1084802.00    13. 340425.250
14. 1360084.00    15. 1149937.00    16. 1429809.00    17. 1241857.00

  YEAR THREE

 1. 1214101.00     2. 1424416.00     3. 1503089.00     4. 1502955.00     5. 1517780.00     6. 1450013.00     7. 1434059.00
 8. 1741012.00     9. 1956191.00    10. 1695337.00    11. 1821530.00    12. 1537905.00    13. 1586125.00    14. 947566.312
15.-392204.312    16. 966827.062    17. 198855.375    18. 774997.687    19. 751705.250    20. 1990511.00    21. 2010437.00
22. 1943717.00    23. 2117259.00    24. 2099249.00    25. 1930896.00    26. 1873678.00    27. 1948965.00    28. 1698731.00

  YEAR FOUR

 1. 1536870.00     2. 1835336.00     3. 1933147.00     4. 1991483.00     5. 2004782.00     6. 2010777.00     7. 1967632.00
 8. 1876052.00     9. 1817544.00    10. 2256307.00    11. 2565303.00    12. 2273481.00    13. 2492822.00    14. 2175811.00
15. 2291037.00    16. 1947332.00    17. 1992720.00    18. 866716.375    19.-489224.250    20. 865187.125    21. 76887.5000
22. 645225.312    23. 595631.875    24. 1085992.00    25. 1060582.00    26. 2629167.00    27. 2706275.00    28. 2683114.00
29. 2546925.00    30. 2835613.00    31. 2875449.00    32. 2792416.00    33. 2678137.00    34. 2643160.00    35. 2540142.00
36. 2745341.00    37. 2692304.00    38. 2509814.00    39. 2414319.00    40. 2479900.00    41. 2135357.00


  THE OPTIMAL FMS SEQUENCE IS AS FOLLOW:


                    YEAR          CONF.        F-VALUES
                     1              5           707226.31
                     2              7          1352506.00
                     3             24          2099249.00
                     4             31          2875449.00
```

Resetting the 16% indirect labor rate back to 6%, now the annual increase of direct labor is assumed to be 18% instead of 8%. The results are listed in Table IX.16. Once again, there is no change in optimal replacement sequence. The price volume combinations are:

	Year One	Year Two	Year Three	Year Four
Part One:	160 - 3800	210 - 3800	260 - 3800	310 - 3800
Part Two:	225 - 2200	275 - 1200	350 - 1600	400 - 1600
Part Three:	300 - 3500	400 - 2700	400 - 3500	500 - 2700

IX.6.6 Machine Capacities of 360,000 hrs.

To see the effect of changes in machine capacity the yearly machine capacities are all decreased from 480,000 hrs. to 360,000 hrs. The results of this change are shown in Table IX.17. Once more, no change in optimal replacement sequence is observed. The price-volume combinations are:

IX.6.6 Machine Capacities of 360,000 hrs.

To see the effect of changes in machine capacity the yearly machine capacities are all decreased from 480,000 hrs. to 360,000 hrs. The results of this change are shown in Table IX.17. Once more, no change in optimal replacement sequence is observed. The price-volume combinations are:

Table IX.15

16% Annual Increase in Unit Indirect Labor Cost
The Optimal Return Values (F-Values) for All Configurations: (Conf. F-Value)

```
  YEAR ONE

 1. 480180.000    2. 545646.000    3. 570568.875    4. 643097.500    5. 707226.312    6. 572645.437   7. -139754.625
 8. 717380.500

  YEAR TWO

 1. 998387.000    2. 1115936.00    3. 1173561.00    4. 1140057.00    5. 1152827.00    6. 1337297.00   7.  1476368.00
 8. 1247803.00    9. 1326185.00   10. 1091377.00   11.-281324.375   12. 1187790.00   13. 340425.250  14.  1492717.00
15. 1485550.00   16. 1561967.00   17. 1389151.00

  YEAR THREE

 1. 1474726.00    2. 1685099.00    3. 1773506.00    4. 1779876.00    5. 1802967.00    6. 1734298.00    7. 1726499.00
 8. 2045430.00    9. 2271674.00   10. 2009363.00   11. 2169209.00   12. 1843398.00   13. 1926635.00   14. 998977.062
15.-392204.312   16. 1069815.00   17. 198855.375   18. 881924.562   19. 858632.125   20. 2317579.00   21. 2359250.00
22. 2291712.00   23. 2452499.00   24. 2446813.00   25. 2308795.00   26. 2246166.00   27. 2334840.00   28. 2062541.00

  YEAR FOUR

 1. 1967894.00    2. 2285512.00    3. 2396711.00    4. 2477313.00    5. 2499728.00    6. 2517335.00    7. 2478818.00
 8. 2373165.00    9. 2321849.00   10. 2798034.00   11. 3130787.00   12. 2837301.00   13. 3098113.00   14. 2741837.00
15. 2918113.00   16. 2477469.00   17. 2557145.00   18. 918127.125   19.-489224.250   20. 968175.062   21. 76887.5000
22. 752152.187   23. 702558.750   24. 1346617.00   25. 1321207.00   26. 3210935.00   27. 3321448.00   28. 3313240.00
29. 3173781.00   30. 3438131.00   31. 3499448.00   32. 3417794.00   33. 3333873.00   34. 3336079.00   35. 3193874.00
36. 3441627.00   37. 3367502.00   38. 3202665.00   39. 3081998.00   40. 3183419.00   41. 2790445.00


     THE OPTIMAL FMS SEQUENCE IS AS FOLLOW:

                        YEAR          CONF.          F-VALUES
                         1              5             707226.31
                         2              7            1476368.00
                         3             24            2446813.00
                         4             31            3499448.00
```

Table IX.16

18% Annual Increase in Unit Direct Labor Cost
The Optimal Return Values (F-Values) for all Configurations: (Conf. F-value)

```
   YEAR ONE

 1. 480180.000    2. 545646.000    3. 570568.875    4. 643097.500    5. 707226.312    6. 572645.437    7.-139754.625
 8. 717380.500

   YEAR TWO

 1. 999624.750    2. 1116976.00    3. 1177698.00    4. 1139961.00    5. 1157202.00    6. 1335838.00    7. 1476660.00
 8. 1246535.00    9. 1326274.00   10. 1091317.00   11.-281324.375   12. 1187382.00   13. 340425.250   14. 1494208.00
15. 1487163.00   16. 1562960.00   17. 1390044.00

   YEAR THREE

 1. 1479028.00    2. 1685997.00    3. 1786545.00    4. 1777860.00    5. 1817743.00    6. 1734556.00    7. 1738652.00
 8. 2040340.00    9. 2271591.00   10. 2004130.00   11. 2169164.00   12. 1841245.00   13. 1927435.00   14. 998917.062
15.-392204.312   16. 1069407.00   17. 198855.375   18. 883162.312   19. 859869.875   20. 2322488.00   21. 2363960.00
22. 2291466.00   23. 2455204.00   24. 2449356.00   25. 2311204.00   26. 2246554.00   27. 2336682.00   28. 2065043.00

   YEAR FOUR

 1. 1975787.00    2. 2286777.00    3. 2428321.00    4. 2471246.00    5. 2532964.00    6. 2513503.00    7. 2510491.00
 8. 2373014.00    9. 2348992.00   10. 2783359.00   11. 3129497.00   12. 2823679.00   13. 3097721.00   14. 2732575.00
15. 2917581.00   16. 2476335.00   17. 2559512.00   18. 918067.125   19.-489224.250   20. 967767.062   21. 76887.5000
22. 753389.937   23. 703796.500   24. 1350919.00   25. 1325509.00   26. 3222621.00   27. 3330054.00   28. 3318111.00
29. 3170437.00   30. 3443375.00   31. 3504454.00   32. 3420757.00   33. 3342390.00   34. 3339219.00   35. 3191515.00
36. 3446170.00   37. 3 69877.00   38. 3208889.00   39. 3081351.00   40. 3185989.00   41. 2796091.00


     THE OPTIMAL FMS SEQUENCE IS AS FOLLOW:

                    YEAR          CONF.         F-VALUES
                     1              5            707226.31
                     2              7           1476660.00
                     3             24           2449356.00
                     4             31           3504454.00
```

	Year One	Year Two	Year Three	Year Four
Part One:	160 - 3800	270 - 3800	260 - 3800	310 - 3800
Part Two:	250 - 1600	300 - 1600	350 - 1600	400 - 1600
Part Three:	350 - 2700	400 - 2700	450 - 2700	500 - 2700

As can be observed, the production volume for each part type for the next four years remains the same, indicating a steady output policy.

IX.6.7 Summary

Some preliminary parametric analysis were performed on the illustrative example. A summary of results is provided in Table IX.18. Although the analysis is limited in scope, all indications show that the replacement policy is quite insensitive to changes with respect to the parameters examined. Also, the output levels under the replacement policy remains relatively stable as well. While the parametric analysis is focused on this illustrative example, the main purpose, above all, is to demonstrate the robustness of the multi-year replacement model. Moreover, one can also observe the complex production environment within which this replacement model is cast. In fact, to derive any meaningful interpretations upon respective time dynamic production elements, a much more comprehensive parametric analysis is needed

While conclusive interpretation could not be established in this sensitivity demonstration, therein lies an important question: "Can the fact that the replacement decisions are insensitive to parametric

Table IX.17

Machine Capacity of 360,000 for the Entire Planning Horizon
The Optimal Return Values (F-Values) for all Configurations: (Conf. F-Value)

```
   YEAR ONE

 1. 446746.562     2. 478748.500     3. 512277.250     4. 602437.500     5. 651142.125     6.-116462.187     7.-139754.625
 8. 644871.750

   YEAR TWO

 1. 906258.625     2. 987895.625     3. 1056698.00     4. 1026102.12     5. 1058218.00     6. 1236628.00     7. 1358912.00
 8. 1164717.00     9. 1218390.00    10.-234437.000    11.-281324.375    12. 330284.250    13. 306991.812    14. 1339819.00
15. 1352693.00    16. 1423538.00    17. 1250728.00

   YEAR THREE

 1. 836958.687     2. 1509907.00     3. 1614340.00     4. 1594199.00     5. 1655046.00     6. 1552531.00     7. 1573907.00
 8. 1833815.00     9. 2099286.00    10. 1865422.00    11. 1996003.00    12. 1693826.00    13. 1756012.00    14.-326836.937
15.-392204.312    16. 212309.312    17. 165421.937    18. 789796.187    19. 766503.750    20. 2093695.00    21. 2135902.00
22. 2082959.00    23. 2235180.00    24. 2230639.00    25. 2063397.00    26. 2042562.00    27. 2113173.00    28. 1844197.00

   YEAR FOUR

 1. 836958.687     2. 2074872.00     3. 2217888.00     4. 2227361.00     5. 2315812.00     6. 2247261.00     7. 2283487.00
 8. 1630233.00     9. 1632418.00    10. 2487262.00    11. 2907728.00    12. 2580718.00    13. 2855343.00    14. 2525666.00
15. 2669280.00    16. 1764560.00    17. 1844881.00    18.-407686.875    19.-489224.250    20. 110669.375    21. 43454.0625
22. 660023.812    23. 610430.375    24. 708850.062    25. 683440.062    26. 2903318.00    27. 3006376.00    28. 2997814.00
29. 2829877.00    30. 3122888.00    31. 3173843.00    32. 3122400.00    33. 2983906.00    34. 3001431.00    35. 2905007.00
36. 3101029.00    37. 3057658.00    38. 2843584.00    39. 2772169.00    40. 2847819.00    41. 1991068.00


     THE OPTIMAL FMS SEQUENCE IS AS FOLLOW:


                      YEAR          CONF.        F-VALUES
                        1             5           651142.12
                        2             7          1358912.00
                        3            24          2230639.00
                        4            31          3173843.00
```

Table IX.18

A Summary of the Price Volume Combinations for Different Parameters

	Part One				Part Two				Part Three			
Base Case Sections:	Year 1	Year 2	Year 3	Year 4	Year 1	Year 2	Year 3	Year 4	Year 1	Year 2	Year 3	Year 4
	160/3800	210/3800	260/3800	310/3800	225/2200	275/2200	325/2200	400/1600	300/3500	400/2700	400/3500	450/3500
6.2	160/3800	210/3800	260/3800	310/3800	225/2200	275/2200	300/3000	350/3000	300/3500	350/3500	400/3500	450/3500
6.3	160/3800	210/3800	260/3800	310/3800	225/2200	275/2200	325/2200	400/1600	300/3500	400/2700	400/3500	450/3500
6.4	160/3800	176/3800	193.6/3800	213/3800	225/2200	275/1600	272.3/2200	333/1600	300/3500	385/2700	423.5/2700	466/2700
6.5(a)	160/3800	210/3800	260/3800	210/3800	225/2200	275/2200	350/1600	400/1600	300/3500	400/2700	400/3500	500/2700
6.5(b)	160/3800	210/3800	260/3800	310/3800	225/2200	275/2200	350/1600	400/1600	300/3500	400/2700	400/3500	500/2700
6.5	160/3800	210/3800	260/3800	310/3800	225/2200	275/2200	350/1600	400/1600	300/3500	400/2700	400/3500	500/2700
6.6	160/3800	210/3800	260/3800	310/3800	250/2200	300/1600	350/1600	400/1600	300/2700	400/2700	450/2700	500/2700

changes be property inherent in the FMS environment?" This is to say, can it be that since the FMS is flexible by nature, it provides freedom to react and to adapt to the various aspects of production demands placed upon the system? Analogous to the shock-absorber of an automobile, the flexibility property behaves in a similar fashion that adjustments are made where appropriate so as to maintain the final outcome.

Figure IX.6 shows the part assignments for configuration (7,10,4,5) in year three with different changes in parameters. Note that while the output levels are identical in the first two cases, there are adjustments in the assignment process. Namely, operation three of part type two is now shifted to machine 4; also, for part type three, while the route remains the same, the amount assigned differs. In fact, the parts assignment for part type three for each of the parametric changes highlights the adjustment capability of the system. Note that the production volume are all identical at 3500, but each has its unique parts assignment. Clearly, the system has adapted to the changes while maintaining the same output. The next chapter will discuss this and other future research.

IX.7 Summary

This chapter has presented the problem structure as well as the solution procedure for the determination of optimal replacement sequence for a multi-year FMS replacement problem. An illustrative example is

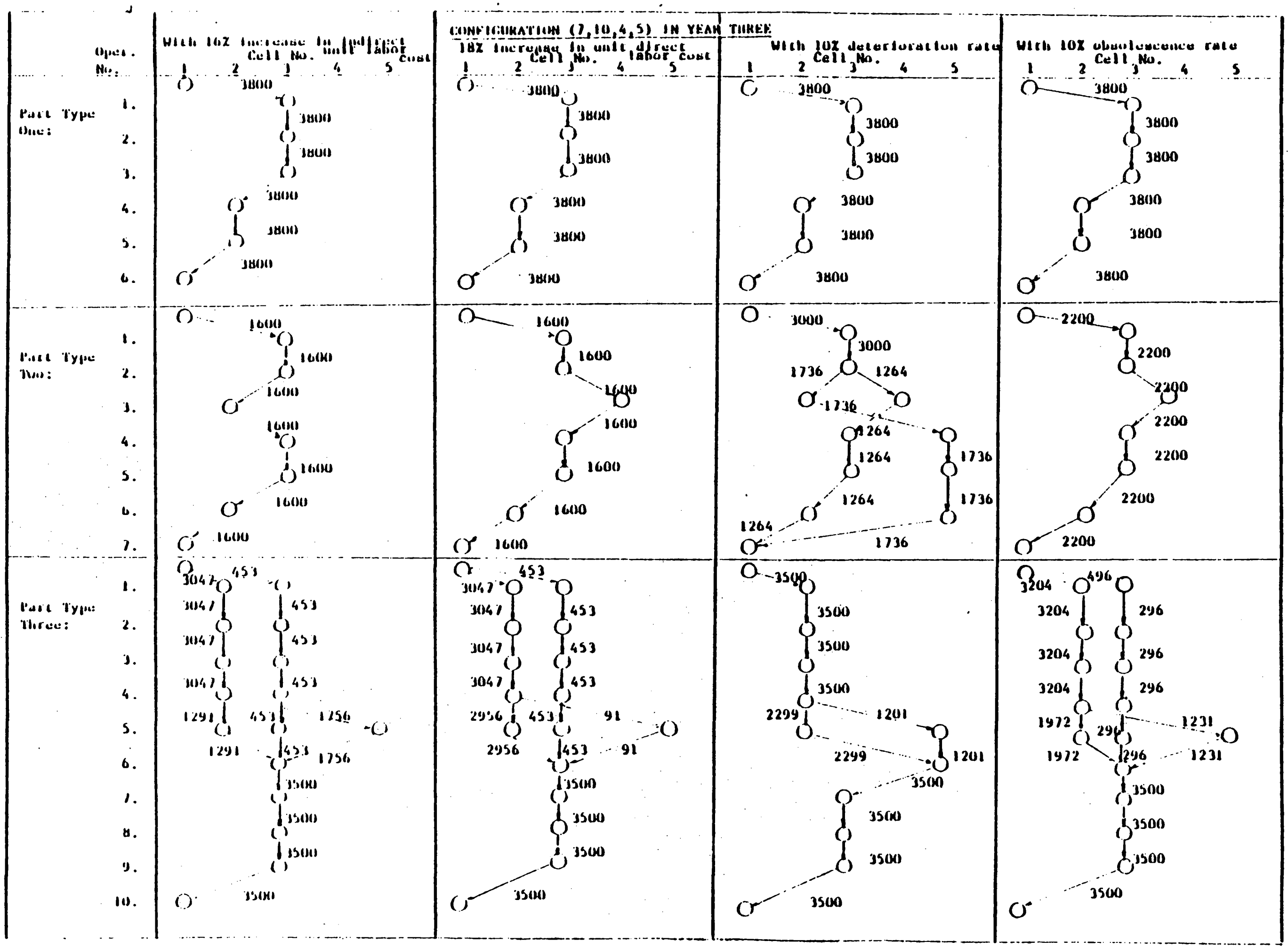


Figure IX.6

Some Evidence of System Flexibility

used to demonstrate the model and most importantly, some of the relevant production economics issues are addressed. A limited parametric experience was also documented in order to establish the possibilities of sensitivity analysis and hence future extensions of this type area. In the next and last chapter, a summary of this research is provided along with recommendations for extensions.

CHAPTER X

SUMMARY AND RECOMMENDATION

In summary, the first chapter discussed the essence of an FMS around which the replacement model is built. Chapters two, three and four outlined the conceptual bases for general replacement problems. Chapter two outlined the nature of equipment replacement chapter three established the factors relevant for replacement decision and chapter four provided a survey of the general replacement literature. Next, chapter five identified the complexity of the FMS replacement environment whose interactive nature defied traditional replacement assumptions. That is, the FMS setting is one of a network of machines producing multiple products, which shares multiple inputs including a vital conveyance system. Chapter six developed a multi-year replacement model suitable for the FMS framework. There were two parts: (i) determination of maximum operating profit with respect to parts routing, parts demand profile, and input resources --for a given FMS configuration, and (ii) determination of optimal FMS sequence over the replacement horizon, this would establish the replacement policy as well as the output policy. Chapters seven, eight, and nine illustrated the problem of parts assignment and the problem of FMS replacement sequence. In these three chapters, relevant issues were highlighted where appropriate.

Thus, in this research, a multi-year replacement model suitable for FMSs has been presented. Special attentions have been given to such considerations as input substitutions, machine utilization, iterrelated production activities and capacity expansion/contraction. While the model is focused on the characteristics of FMSs, the model's general framework enables it to be applied to many other production systems. For example, a transfer line system can be viewed as a special case of an FMS which has no pooling and no feedback of material. As such, the replacement policy of transfer lines or production systems of a serial nature can be similarly examined. Likewise, a conventional job shop environment can also be viewed as an FMS without the automated material handling system. The analysis of replacement policy of such system also follows similarly. Further, this model can be utilized to study the effects of machine groupings.

From an adjustment-to-change perspective, this model can examine the effects of changes wth respect to input costs. For example, one can utilize this model to approach the question: "What would be the appropriate course of action if the unit cost of skilled labor increases drastically in the future?" Such issues (and others alike) about the changes of input values is a relevant aspect of production planning. For this directly addresses the issue of input substitution and, more importantly, the technology level which the system should operate at. Closely related and of equal significance is the planning strategy for the changes in the product demand as well as product mix. This model can be extended to study the replacement policy under such a scenario; the issue of capacity planning falls under this category.

While the economic interpretations and the analysis of the results presented in this work are deduced freom a contrived example and with limited parametric experience, it is believed that fruitful results can be obtained based on a set of more realistic parameters and a more comprehensive sensitivity analysis. As stated previously, the intent of the illustrative example is not so much to arrive at conclusive assessments, but to show both the possibilities and the directions for such an analysis.

To conclude, a multi-year replacement model suitable for FMSs or systems of similar multiple inputs-multiple outputs-multiple machines interactive nature is developed. The model is believed to be robust and could be used as a planning tool. More importantly, the emphasis of this research has been conceptual and it orients towards the many production economic issues plaguing today's production planners. To that end, this work intends to provoke thoughts and interests in the long term design and planning of manufacturing systems under the light of equipment replacement. This dissertation concludes with the following recommendations fore future research in this topic area.

(i) Performance of a comprehensive sensitvity analysis on the the vital production/ economic factors. It is believed that fruitful interpretations on the vital parameters are likely.

(ii) Comparison of FMS with other production systems. This, in fact, follows the preceding recommendation. That is, this model could help provide some interesting insights to such questions as --Is transfer system preferred to FMS? Why and Why not?; Under what environment does FMS perform superior to other systems and so on.

(iii) Creation of an unstable market environment with fluctuations in product demand as well as changes in product mix so as to examine the replacement policy under such a scenario.

(iv) Analyzing the impact of the materials handling system. That is, one can treat the materials handling system as another machine and the analysis could proceed as such. Such issue as the number of AGVs can be approached under this scenario.

(v) The large size of this problem places tremendous computational burden on exact solution procedures. Some effocoemt bounding strategy to this problem appears to be a need if large realistic problems are to be solved. Again, the curse of dimensionality does plague the solution process.

(vi) Other issues such as budget, set-up times, inventory costs, etc. are appropriate elements to be further incorporated.

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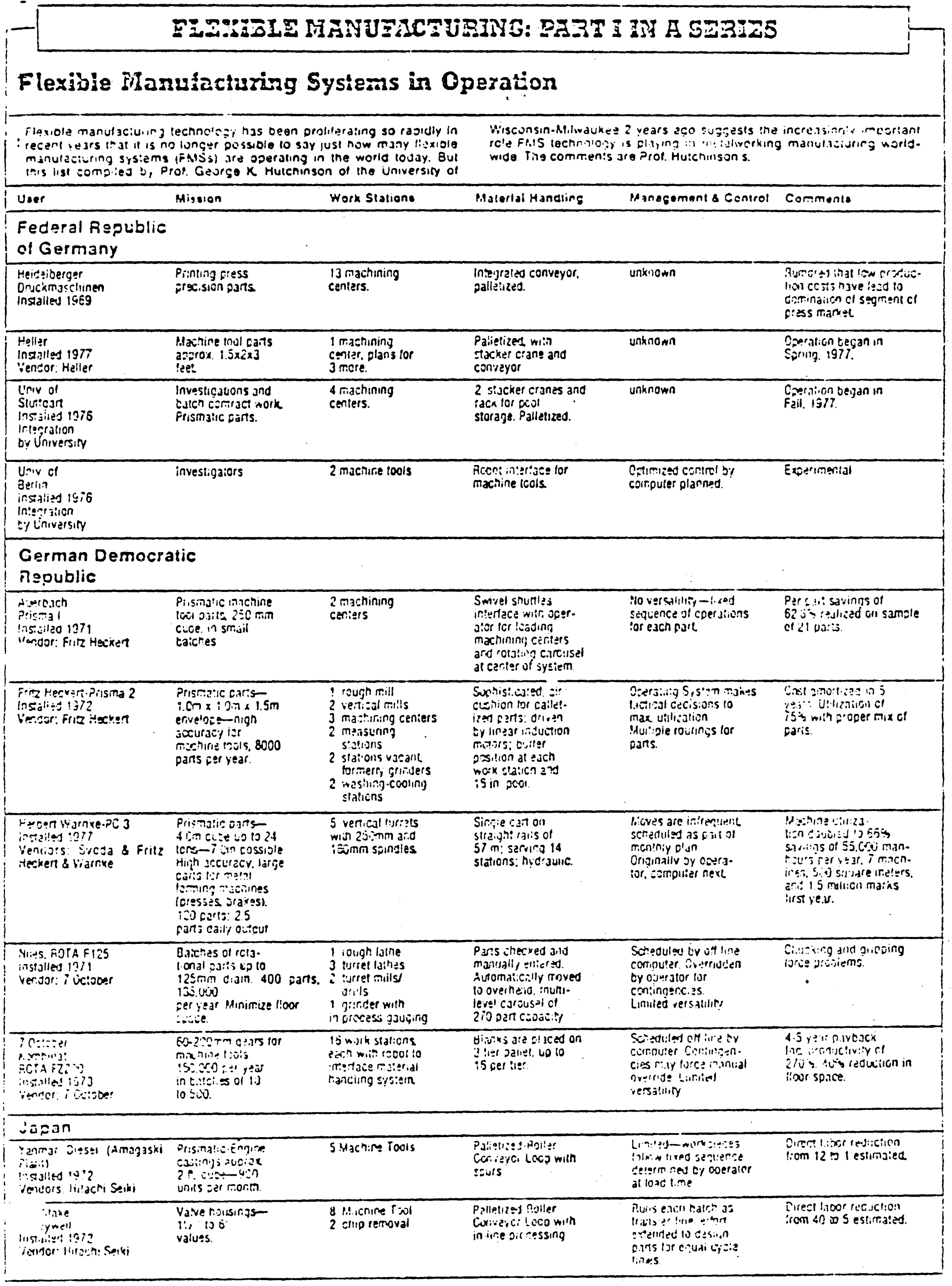
APPENDICES

APPENDIX I



FLEXIBLE MANUFACTURING: PART I IN A SERIES

Flexible Manufacturing Systems in Operation

Flexible manufacturing technology has been proliferating so rapidly in recent years that it is no longer possible to say just how many flexible manufacturing systems (FMSs) are operating in the world today. But this list compiled by Prof. George K. Hutchinson of the University of Wisconsin-Milwaukee 2 years ago suggests the increasingly important role FMS technology is playing in metalworking manufacturing worldwide. The comments are Prof. Hutchinson's.

User	Mission	Work Stations	Material Handling	Management & Control	Comments
Federal Republic of Germany					
Heidelberger Druckmaschinen Installed 1969	Printing press precision parts.	13 machining centers.	Integrated conveyor, palletized.	unknown	Rumored that low production costs have lead to domination of segment of press market.
Heller Installed 1977 Vendor: Heller	Machine tool parts approx. 1.5x2x3 feet.	1 machining center, plans for 3 more.	Palletized, with stacker crane and conveyor	unknown	Operation began in Spring, 1977.
Univ. of Stuttgart Installed 1976 Integration by University	Investigations and batch contract work. Prismatic parts.	4 machining centers.	2 stacker cranes and rack for pool storage. Palletized.	unknown	Operation began in Fall, 1977.
Univ. of Berlin installed 1976 Integration by University	Investigators	2 machine tools	Robot interface for machine tools.	Optimized control by computer planned.	Experimental
German Democratic Republic					
Auerbach Prisma I Installed 1971 Vendor: Fritz Heckert	Prismatic machine tool parts, 250 mm cube, in small batches	2 machining centers	Swivel shuttles interface with operator for loading machining centers and rotating carousel at center of system.	No versatility—fixed sequence of operations for each part.	Per part savings of 62.5% realized on sample of 21 parts.
Fritz Heckert-Prisma 2 Installed 1972 Vendor: Fritz Heckert	Prismatic parts—1.0m x 1.0m x 1.5m envelope—high accuracy for machine tools, 8000 parts per year.	1 rough mill 2 vertical mills 3 machining centers 2 measuring stations 2 stations vacant, formerly grinders 2 washing-cooling stations	Sophisticated, air cushion for palletized parts; driven by linear induction motors; buffer position at each work station and 15 in pool.	Operating System makes tactical decisions to max. utilization. Multiple routings for parts.	Cost amortized in 5 years. Utilization of 75% with proper mix of parts.
Herbert Warnke-PC 3 Installed 1977 Vendors: Sveda & Fritz Heckert & Warnke	Prismatic parts—4.0m cube up to 24 tons—7.0m possible. High accuracy, large parts for metal forming machines (presses, brakes). 120 parts: 2.5 parts daily output	5 vertical turrets with 250mm and 160mm spindles.	Single cart on straight rails of 57 m; serving 14 stations; hydraulic.	Moves are infrequent, scheduled as part of monthly plan. Originally by operator, computer next.	Machine utilization doubled to 66% savings of 55,000 man-hours per year, 7 machines, 500 square meters, and 1.5 million marks first year.
Nles, ROTA F125 installed 1971 Vendor: 7 October	Batches of rotational parts up to 125mm diam. 400 parts, 135,000 per year. Minimize floor space.	1 rough lathe 3 turret lathes 2 turret mills/drills 1 grinder with in process gauging	Parts checked and manually entered. Automatically moved to overhead, multi-level carousal of 270 part capacity	Scheduled by off line computer. Overridden by operator for contingencies. Limited versatility	Chucking and gripping force problems.
7 October Kombinat ROTA FZ200 Installed 1973 Vendor: 7 October	60-200mm gears for machine tools 150,000 per year in batches of 10 to 500.	16 work stations, each with robot to interface material handling system.	Blanks are placed on 3 tier pallet, up to 15 per tier.	Scheduled off line by computer. Contingencies may force manual override. Limited versatility	4-5 year payback Inc. productivity of 270%. 40% reduction in floor space.
Japan					
Yanmar Diesel (Amagaski Plant) Installed 1972 Vendors. Hitachi Seiki	Prismatic-Engine castings approx. 2 ft. cube—900 units per month.	5 Machine Tools	Palletized-Roller Conveyor Loop with spurs	Limited—workpieces follow fixed sequence determined by operator at load time	Direct labor reduction from 12 to 1 estimated.
Yamatake Honeywell Installed 1972 Vendor: Hitachi Seiki	Valve housings—1½" to 6" values.	8 Machine Tool 2 chip removal	Palletized Roller Conveyor Loop with in-line processing	Runs each batch as transfer line, effort extended to design parts for equal cycle times.	Direct labor reduction from 40 to 5 estimated.

FLEXIBLE MANUFACTURING: PART I IN A SERIES

User	Mission	Work Stations	Material Handling	Management & Control	Comments
North American Rockwell Installed 1973 Vendor: Kearney & Trecker	Cast iron differential carriers for trucks in lots of 10 to 50. 33 parts. 1.5 foot cube 8 parts simultaneously. 24,000 per year.	3 Machining Centers	Same as Allis Chalmers except a simple loop with spur rather than a network.	Same as Allis Chalmers	Original installation included inspection station. Greatly reduced set-up time and batch sizes, reducing WIP.
Avco Lycoming Installed 1976 Vendor: Kearney & Trecker	Aluminum aircraft engine (4 and 6 cylinder) crankcase halves	2 Simplex Multi-Spindle Head Indexers 1 Duplex Multi-Spindle Head Indexer 9 Machining Centers	Same as Allis Chalmers except some machines have a single position queue.	Same as Allis Chalmers. Every operation has alternative work station.	Reduced 30 set ups per part to 5. Direct labor and floor space reduced. Largest FMS in terms of work stations.
Cummins Engine Lakewood, NY	Produce cam-follower levers and housings from raw castings.	1 chain branch 2 special purpose mills 2 inspection stations 2 mills 1 drill 1 deburr 1 washer	4 Unimate robots Internal storage conveyors	Continuous production	Product changes and high capital costs eliminated hand automation.
International Harvester Installed 1980 Vendor: White-Sundstrand	4 fast cube cast iron parts of 6 families with 4-5 variations of each	4 Horizontal Machining Centers 4 Tilt Head Machining Centers	Straight track with 2 shuttle cars	See Caterpillar system	
General Dynamics Convair Installed, Phase I 1980 Vendor: White-Sundstrand	4 foot cube aircraft and missile parts	4 5 axis Machining Centers 4 4 axis Machining Centers	Straight track with 1 shuttle car	See Caterpillar system	Phase II is planned to have 5 machining centers and a second shuttle.
Chevrolet Reported 1979 Vendors: Auto-Place robot and Opto Sense optics	Testing and visual inspection of value covers of 2 types	Dial index with 6 dual fixture test station	Index table & robot	Continuous production	Included because of visual inspection. 1200 parts per hour with one man versus 300 with 4 men on 2 lines.
Massey Ferguson Detroit, MI Installed 1979 Vendors: Massey Ferguson & Unimate robots	4 sizes of planetary pinion gears, run in batches, from 3½" to 7" O.D.	2 vertical checkers 2 shear speeds 3 gear shavers	3 robots; local storage	Choice of batch size. Internal storage and alternate programs for robot give graceful degradation.	Robots est. to be 25% more productive than men. 1½ years to payback w/o reduction savings in WIP.
Xerox Rochester, NY Reported 1979 Vendor: Unimate robots	Family of copper fuser rolls for duplicators with frequent model changes.	2 double end lathes 1 braving 1 grinding 1 broaching 1 turning	3 robots and conveyor	Control from central station to robots.	Capacity of 100,000 parts per year.
General Electric Reported 1979 Vendor: Prob. Robot	Electric motor brush boxes	1 mill 1 drill & tap		Continuous production	Robot holds part throughout cycle, i.e. no fixture. Payoff in 13 months
Unknown Installed 1980 Vendor: Giddings & Lewis	Production of a family of 8 parts, large prismatic weldments, up to 22 feet.	6 Horizontal bores 1 special purpose bore	Drag chain loop, workpieces mounted on carts. Lift and carry to MT.	Workpieces go through 2 sequences. Work stations dynamically assigned.	Expected to run with 3-4 men, increase MT utilization.
Unknown Installed 1981 Vendor: Giddings & Lewis	Produce prismatic parts of approximate 3 foot cube	4 table horizontal bores	Palletized workpieces on single straight track cart	Workpieces dynamically assigned based on system status, workload, tool life.	
Crysler Lima, OH Installed 1979 Vendor: Cincinnati Milacron	Produce turret and hull XM1 tank pads, very large steel, up to 40 tons.	1 spec. adapt. horiz. mach. ctr. 1 cluster head changer 1 special design 1 spec. adapt. vert. mach. ctr.	Palletized, moved in each step on single line. Hydro-static support for pallets	All machines are NC and no hard tooling, minimum decision making required.	Expect substantial labor saving in material handling
Crysler Lima, OH Installed 1979 Vendor: Cincinnati Milacron	Produce a narrow family of torsion bar housings, approx. 3 foot cube	2 special design 1 horiz. Machine Center 1 Head Changer	Palletized parts on linear, powered roller conveyor.	See Crysler above.	Expect substantial labor savings, as above.

FLEXIBLE MANUFACTURING: PART I IN A SERIES

User	Mission	Work Stations	Material Handling	Management & Control	Comments
Yamazaki Nagoya Installed 1977 Vendor: Yamazaki	Machine Tool parts	1 machine tool Multiple Work Stations	Multiple Work Stations—MT moves to work	unknown	Plans for automated tool flow, included tool room.
Fujitsu Fanuc (4 systems) Installed 1977 Vendor: Fujitsu Fanuc	Batches of parts—10 inch cube	5 machine tools	FANUC 2 Robot loads and repositions parts from a manually loaded input queue.	Fixed sequence of single operations.	Cost performance increases of 420% due to NC and additional 29% due to robot are estimated.
Fujitsu Fanuc Installed 1970 Vendor: Fujitsu Fanuc	Batches of rotational parts—10 inch cube, 151 parts.	8 lathes	Kawasaki Robot on overhead rail loads lathes, manual movement between lathes.	Robot moves to next activity FCFS. Single operation on each lathe.	Appears to have excess robot capacity.
Sweden					
ASEA Vastarras Reported 1979 Vendor: Unknown	Produce 3 parts, each in six sizes, for electric motors. Run 3 shifts with 1 manned.	1 turning center 1 rotary table grinder 2 turret drills	Cincinnati Milacron robot. Internal storage Conveyor	Parts of a given size are batch produced in 200 minimum lots. Manned one shift, unmanned two.	Large internal storage required for unmanned operation.
ASEA (6) Installed 1977 Vendor: Kearney & Trecker	3 shift operation with 1 shift manned. Very small batches and wide variety.	1 machining center	10 pallets move sequentially, can hold more than one part.	Once operator loads 2 systems during day and all 6 run remaining 2 shifts with a single supervisor	Estimated 9 to 5 reduction in labor.
Norway					
SINTIF Trondheim Installed 1977 Vendor: SINTIF	Experimental. Operate 24 hours with one manned shift.	1 lathe 1 mill 1 drill 1 machining Center 1 Cincinnati Milacron robot	Robot moves work between machines and rack storage	Control computer attempts to optimize operations.	Project part of an attempt to disperse industry, economics are not clear.
United States					
Ingersol Rand-Omniline Installed 1972 Vendor: White-Sundstrand	130 parts, generally in batches, but service parts as well. 3 foot cube. 70,000 per year, up to 15 parts simultaneously.	2 4-axis mills 2 5 axis mills 2 4-axis drills	Roller conveyor of palletized parts. Loop with buffer position at each machine.	Fixed sequence within system. Foreman balance workload by dispatching. Has multiple alternative routings.	50% reduction in direct labor. Up to 70% reduction of part costs.
Caterpillar Installed 1974 Vendor: White-Sundstrand	Cast iron case and cover for tractor transmission. 6 parts, 1200 per year. Approx. 3 foot cube.	5 Omnimills 2 G&L turret lathes 3 Omnimills 1 DEA inspection	Palletized parts. 2 carts move parts between machines and load area, which also serves as buffer.	Fixed sequence, due to tuning limitations. Production to monthly master plan.	Tooling constraints. Carts are weak link in system, replacement planned.
Sundstrand Aviation Installed 1967 Vendor: White-Sundstrand	Aluminum pump parts and magnesium castings for aircraft speed drive housings.	8 OM-2 Omnimill Machining Centers 2 Multiple Spindle drilling machines	Palletized workpieces have code to direct to next station on roller conveyor (power and free).	Limited versatility, fixed sequence at introduction to system.	Replaces est. 100 conventional machines.
Allis Chalmers Installed 1971 Vendor: Kearney & Trecker	Produces cast iron tractor parts for direct assembly 23,000 per year. Approx. 3 ft. cube.	5 Machining Centers 1 Mill 4 Duplex multi spindle head indexers	Palletized workpieces moved under computer control to work station on towed carts.	Work stations dynamically assigned by computer to balance load.	System incrementally installed. Work max changed drastically between design and use.

APPENDIX II

Determination of the optimal FMS configuration sequence -- A backward recursive formulation

Define $f_{i,j,t}$ as the optimal terminal wealth of the FMS (i,j,t) if an optimal replacement policy is pursued from hereon until T.

The recursion relationships start at the end of the planning horizon and backtrack to the present.

Starting Point:

For t = T,

$$\text{(A)} \qquad f_{i,j,T} = \{-W_{ijT}\ (r) + (1-\rho)\ (OP_{ijT}-D_{ijT}\}$$

Recursive Relationship:

For t = 1, 2, ..., T-1

$$f_{\hat{i},\hat{j},\hat{t}} \quad \begin{array}{ll} \text{(B)} & \text{if } (\hat{i},\hat{j},\hat{t}) \in \{J_1, \hat{t}\} \\ \\ \text{(C)} & \text{Otherwise} \end{array}$$

$$\text{(B)}\ f_{\hat{i},\hat{j},\hat{t}} = \sum_{t=\hat{t}}^{T-1} \{-W_{ij\hat{t}}\ (r) + (1-\rho)(OP_{ij\hat{t}} - D_{ij\hat{t}})\}(1+r)^{T-\hat{t}}$$

(C) $f_{\hat{i},\hat{j},\hat{t}} = \{-W_{\hat{i}\hat{j}\hat{t}}\ (r) + (1-\rho)(OP_{\hat{i}\hat{j}\hat{t}} - D_{\hat{i}\hat{j}\hat{t}})\}(1+r)^{T-\hat{t}}$

$$V\ \hat{i} = 1, 2, \ldots, I \qquad \hat{j} = 2, 2, \ldots, \hat{t} \qquad \hat{t} = 1, 2, \ldots, T-1 \qquad + \underset{V\ (i,j,t)\ \varepsilon\ I_{\hat{i}\hat{j}\hat{t}-1}}{\overset{f_{i,j,t}}{\mathrm{MAX}}}$$

$I_{2,\hat{t}}$ is all the feasible changes for configuration $\hat{i}$

<u>Stopping Criterion:</u>

MAX: $\{f_{\hat{i},11} \quad V\ i = 1, 2, \ldots, I\}$

APPENDIX III

```
       COMMON/WAR/NBASIC(150),RHS(150),NUPPER(150),SURROG(150),AVALU
C     DOUBLE PRECISION IS USED
C
C
CC
C     /*ROUTE PRINT VM2.INDC105
      DIMENSION K(10),T(10,10,10),DD(10,10),XDL(20),POB(10)
      DIMENSION XIDL(20),XMIS(20),XMANT(20),PB(10),NON(6)
      DIMENSION P(10,10),XLL(10,10),XUL(10,10),OBJ(150)
      DIMENSION IID(10,10,10,10),A(150,150),B(150)
      DIMENSION BH(150),TEMP(150),NFLAG(300),XMIN(150),XOPT(150)
      DIMENSION XUB(150),XMAX(150),Y(150),BINV(150,150),RH(20)
      DIMENSION F(6,100),OPPF(6,100)
      DIMENSION TID(6,100),INDE(20),ICH(20)
      DIMENSION IRB(20),IDE(20),ITORE(20),TIMC(10,10,20),IONE(100)
      DIMENSION DEP(6,100),MVALUE(6,100),ELEM(6,100,2),ITWO(100)
      DIMENSION PB2(10),TDETF(20),DIDL(20),DDL(20),DMIS(20)
      DIMENSION DMANT(20),XLL2(10,10),XUL2(10,10),MDE(20),MCH(20)
      DIMENSION TIDL(20),TDL(20),TMIS(20),TMANT(20),PB3(10)
      DIMENSION OIDL(20),ODL(20),OMIS(20),OMANT(20),TRH(20),CCOST(6,100)
      DIMENSION TRH2(20),TRH3(20),TOBS(20),NCON(6),TDUAL(150)
      DIMENSION P2(10,10),P3(10,10),XLL3(10,10),XUL3(10,10),TOBJ(150)
      DIMENSION PB4(10),XLL4(10,10),XUL4(10,10),P4(10,10),TRH4(20)
      REAL IDLC2,DLC2,MISC2,MANTC2
      REAL IDLC4,DLC4,MISC4,MANTC4
C
      REAL IDLC3,DLC3,MISC3,MANTC3
C
C
C
C
C ****************************************************************
C *                                                              *
C * 1.TOTAL NUMBER OF PARTS IN THE FMS- IPA                      *
C * 2.TOTAL NUMBER OF OPERATIONS PER PART - K(P)                 *
C * 3.TOTAL NUMBER OF MACHINE STATIONS INCLUDING U/UL STATION    *
C *                                           - MC               *
C * 4.COST OF AGV- PER UNIT DISTANCE TRAVELLED- W                *
C * 5.AGV UTILIZATION                         - ALPHA            *
C * 6.OPERATION TIMES PER M/C STATION PER PART- T(I,J,M)         *
C * 7.DISTANCE MATRIX                         - D(I,J)           *
C * 8.DIRECT LABOR,                           - TDL(I)           *
C *   INDIRECT LABOR,                         - TIDL(I)          *
C *   MISCELANEOUS,                           - TMIS(I)          *
C *   MAINTENANCE                             - TMANT(I)         *
C * 9.UNIT COSTS OF DIRECT,                   - X$DL             *
C *                 INDIRECT LABOR,           - X$IDL            *
C *                 MISCELANEOUS,             - X$MIS            *
C *                 MAINTENANCE               - X$MANT           *
C *   DEMAND PROFILE:                                            *
```

```
C *10.   NUMBER OF PRICE-BREAKS FOR EACH PART                          *
C *                                    TYPE    - PB(I)                  *
C *                                                                     *
C *11.   UNIT SELLING PRICE OF ITH PART AT THE                          *
C *                            JTH PRICE-BREAK- P(I,J)                  *
C *      LOWEST PRODUCTION LIMIT OF ITH PART                            *
C *                  AT THE JTH PRICE-BREAK    - XLL(I,J)               *
C *                                                                     *
C *      HIGHEST PRODUCTION LIMIT OF ITH  PART                          *
C *                  AT THE JTH PRICE-BREAK    - XUL(I,J)               *
C *   RESOURCES ALLOCATION                                              *
C *12.   UPPER LIMIT OF DIRECT LABOR           - TRH(1)                 *
C *13.   UPPER LIMIT OF INDIRECT LABOR         - TRH(2)                 *
C *14.   UPPER LIMIT OF MISCELANEOUS INPUTS    - TRH(3)                 *
C *15.   UPPER LIMIT OF MAINTENANCE INPUT      - TRH(4)                 *
C *16.   UPPER LIMIT OF MACHINE 2              - TRH(5)                 *
C *17.   UPPER LIMIT OF MACHINE 3              - TRH(6)                 *
C *18.   UPPER LIMIT OF MACHINE 4              - TRH(7)                 *
C *19.   UPPER LIMIT OF MACHINE 5              - TRH(8)                 *
C *20.   UPPER LIMIT OF MACHINE 6              - TRH(9)                 *
C *21.   UPPER LIMIT OF MACHINE 7              - TRH(10)                *
C *22.   UPPER LIMIT OF AGV                    - TRH(11)                *
C *   MACHINE VALUES                                                    *
C *   INCUMBENTS: YEAR ONE                                              *
C *23.   VALUE OF MACHINE TWO AT YEAR ONE      - MVALUE(2,1)            *
C *24.   VALUE OF MACHINE THREE AT YEAR ONE    - MVALUE(3,1)            *
C *               YEAR TWO                                              *
C *25.   VALUE OF MACHINE TWO AT YEAR TWO      - MVALUE(2,2)            *
C *26.   VALUE OF MACHINE THREE AT YEAR TWO    - MVALUE(3,2)            *
C *   CHALLENGERS:YEAR ONE                                              *
C *27.   VALUE OF MACHINE SIX AT YEAR ONE      - MVALUE(6,1)            *
C *28.   VALUE OF MACHINE SEVEN AT YEAR ONE    - MVALUE(7,1)            *
C *               YEAR TWO                                              *
C *29.   VALUE OF MACHINE SIX AT YEAR TWO      - MVALUE(6,2)            *
C *30.   VALUE OF MACHINE SEVEN AT YEAR TWO    - MVALUE(7,2)            *
C *                                                                     *
C *                                                                     *
C **********************************************************************
C
C
C   THE FOLLOWING READ STATEMENTS READ IN NUMBER OF PART TYPES,
C   NUMBER OF OPERATIONS PER PART TYPE, TOTAL NUMBER OF MACHINES
C   IN THE FMS, COST PER UNIT TRAVEL OF AGV AND THE AGV UTILIAZATION
C   RATE.
      READ(5,*)IPA
      READ(5,*)(K(I),I=1,IPA)
      READ(5,*)MC
      READ(5,*)W
      READ(5,*) ALPHA
C
```

```
C
C
C
C       ****NOTE THAT FREE FORMAT IS USED FOR ALL ENTRIES****
C
HOLD     DATA     D1  08/04/83  4:52 101__D      F 80     1823 RECS    VA TECH     PRINTED 08/04/83 05:06     PAGE 003

C       ****IF A CERTAIN MACHINE STATION CANNNT PERFORM A PARTICULAR
C            OPERATION, ENTER THE VALUE OF 999****
C
C            (THIS WILL HELP LATER FOR THE IDENTIFICATION OF MATERIAL
C                                                               FLOW)
C
C     **NICUM - DENOTES THE TOTAL NUMBER OF DEFENDERS**
C
      NICUM=2
C
      I7=MC+NICUM
C   THE FOLLOWING READS THE OPERATION TIMES PER MACHINE PART
      DO 10 I=1,IPA
      IKK=K(I)
      DO 10 J=1,IKK
  10  READ (5,*)(TIMC(I,J,M),M=1,I7)
C
C
C   THE FOLLOWING READS THE DISTANCE BETWEEN MCHINES
      DO 20 I=1,MC
 20   READ(5,*)(DD(I,J),J=1,MC)
C
C
C
C
C
C   THE FOLLOWING READS THE CONSUMPTION RATE OF RESPECTIVE INPUTS
C   PER UNIT OUTPUT OF THE RESPECTIVE MACHINE
C
C
      DO 30 I=1,I7
  30  READ(5,*)TDL(I),TIDL(I),TMIS(I),TMANT(I)
C
C
C
C            THE UNIT COST OF RESPECTIVE INPUTS ARE DEFINED AS:
C
C     *** UNIT COST OF DIRECT LABOR -X$DL
C          UNIT COST OF INDIRECT LABOR -X$IDL
C             UNIT COST OF MISCELLANOUS -X$MIS
C               UNIT COST OF MAINTENANCE -X$MANT***
C
```

```
C
C
      READ(5,*)X$DL,X$IDL,X$MIS,X$MANT
C
C
C     READING DEMAND PROFILE
C
C
C     SINCE THE PRICE-VOLUME RELATIONSHIP IS DESCRIBED USING
C            STEP-FUNCTION, THERE ARE A FINITE NUMBER OF PRICE-
C                 BREAKS DENOTED AS PB(PA)
C
C
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      READ(5,*)(PB(I),I=1,IPA)
      DO 40 I=1,IPA
      JPB=PB(I)
C
C
C
C
C
C
C    THE FOLLOWING READS THE PRICE OF A GIVEN PART AT THE CORRESP
C    ONDING VOLUME LEVEL (PRICE-BREAK); ALSO THE UPPER AND LOWER
C    OUTPUT LIMIT AT THIS PRICE IS READ
C
C
      DO 40 J=1,JPB
   40 READ(5,*)P(I,J),XLL(I,J),XUL(I,J)
      NNEW=2
      I9=4+MC+NNEW
C
C   THE FOLLOWING READS THE UPPER LIMIT ON THE AVAILABILITY OF
C   THE RESPECTIVE RESOURCES
C
C
C
      DO 49 I=1,I9
   49 READ(5,*) TRH(I)
      IFLAG=0
C   IFLAG AND EPS ARE PARAMETERS FOR THE L.P. SUBROUTINE
      EPS=0.00001
      JT=1
      I=1
      J1=JT+1
C   THE MACHINE VALUES ARE BEING READ HERE
C    NICUM DENOTES THE NUMBER OF INCUMBENTS
C    NNEW DENOTES THE NUMBER OF CHALLENGERS FOR YEAR ONE
```

```
      DO 93 N4=JT,J1
      DO 94 N2=1,NICUM
      N3=N2+1
 94   READ(5,*)MVALUE(N4,N3)
      DO 92 N5=1,NNEW
      N6=N5+MC
      READ(5,*)MVALUE(N4,N6)
C
  92  CONTINUE
 93   CONTINUE
C
C
C
C*********************************************************************
C*********************************************************************
C******       THE MAXIMUM OPERATING PROFIT FOR THE DIFFERENT     ******
C******          FMS IN YEAR ONE ARE COMPUTED IN THE FOLLOWING   ******
C*********************************************************************
C*********************************************************************
C
```

```
C
      WRITE(6,555)
555    FORMAT(25X,'FMS CONFIGURATIONS IN YEAR ONE')
      NDE=0
      NCH=0
C     THE FMS CONFIGURATION WHERE NO CHALLENGERS EXIST IS
C        FIRST COMPUTED
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2001
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
2001  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
C     DO 4353 I=44,52
C     FSUM=0.
C     DO 4352 J=1,82
C     FSUM=FSUM+A(I,J)*XOPT(J)
C4352    CONTINUE
C     WRITE(6,*)FSUM
C4353    CONTINUE
      OPPF(1,1)=OPT
      DO 234 J=1,NICUM
 234  MDE(J)=J+1
```

```
      DO 233 J=1,NNEW
  233 MCH(J)=MC+J
C     THE FOLLOWING COMPUTES THE ONE-DEFENDER/ONE-CHALLENGER CASE
      I=1
      NDE=1
      NCH=1
      DO 414 J=1,NICUM
      DO 414 M=1,NNEW
      I=I+1
      IDE(1)=MDE(J)
      ICH(1)=MCH(M)
      IRB(1)=MCH(M)
      ITORE(1)=MDE(J)
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF (INFEA.EQ.0)GOTO 2002
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
 2002 CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT)
      OPPF(1,I)=OPT
  414 CONTINUE
C THE FOLLOWING FOOLOWING COMPUTES THE TWO-DEFENDERS/ONE-
C  CHALLENGER CASE
C
C
      NDE=2
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      NCH=1
      DO 411 M=1,NNEW
      I=I+1
      IDE(1)=MDE(1)
      IDE(2)=MDE(2)
      ICH(1)=MCH(M)
      IRB(1)=MCH(M)
      IRB(2)=99
      ITORE(1)=MDE(1)
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2003
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
 2003 CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
```

```
     *XMIS,XMANT,INFEA)
      OPPF(1,I)=OPT
 411  CONTINUE
C
C THE FOLLOWING COMPUTES THE TWO-CHALLENGERS/TWO-DEFENDERS CASE
C
C
      NDE=2
      NCH=2
      I=I+1
      IDE(1)=MDE(1)
      IDE(2)=MDE(2)
      ICH(1)=MCH(1)
      ICH(2)=MCH(2)
      IRB(1)=MCH(1)
      IRB(2)=MCH(2)
      ITORE(1)=MDE(1)
      ITORE(2)=MDE(2)
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2004
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
C     T=2
 2004 CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
      OPPF(1,I)=OPT
      NCON(1)=I
      KI=MC+2
C
C
C
C*****************************************************************
C*****************************************************************
C******      THE FOLLOWING COMPUTES THE MAXIMUM OPERATING        ******
C******           PROFIT FOR ALL FMS CONFIGURATIONS IN YEAR TWO  ******
HOLD     DATA     D1  08/04/83  4:52 101__D       F 80    1823 RECS    VA TECH    PRINTED 08/04/83 05:06    PAGE 007

C*****************************************************************
C*****************************************************************
C
C    HERE THE RELEVANT PARAMETERS ARE UPDATED FOR THE SECOND YEAR
C
C
      WRITE(6,444)
 444  FORMAT(25X,'FMS CONFIGURATIONS IN YEAR TWO')
```

```
      NNEW=NNEW*2
      JT=2
       W=W*1.1
C*****************************************************
C**    ENTER DATA IN THE FOLLOWING ORDER            **
C**  1. DETERIORATION RATES OF RESPECTIVE MACHINES**
C**  2. DETERIORATION RATES OF DIRECT LABOR FOR     **
C**      RESPECTIVE MACHINES  **
C**  3. DETERIORATION RATES OF DIRECT LABOR FOR     **
C**      RSPECTIVE MACHINES  **
C**  4. DETERIORATION RATES OF MISCELLANEOUS        **
C**      INPUTS FOR RESPECTIVE MACHINES             **
C**  5. DETERIORATION RATES FOR MAINTENANCE         **
C**  6. OBSOLESCENCE RATES FOR RESPECTIVE MACHINES**
C**          OPERATIONS   **
C**  7. THE NUMBER OF PRICE-BREAKS PER PART TYPE    **
C**  8. OBSOLESCENCE RATES FOR INDIRECT LABOR  **
C**        FOR RESPECTIVE MACHINES      **
C**  9. OBSOLESCENCE RATES FOR MISCELLANEOUS  **
C**     INPUTS FOR RESPECTIVE MACHINES  **
C**  10.OBSOLESCENCE RATES FOR MAINTENANCE FOR      **
C**     RESPECTIVE MACHINES**
C**  11.THE PRICE-VOLUME RELATIONSHIP**
C**  12.UNIT COST OF IDIRECT LABOR, DIRECT**
C**       LABOR, MISCEL. AND MAINTENCE FOR YEAR TWO**
C**  13.THE UPPER LIMITS OF RESOURCES (FIRST FOUR ON**
C**      INPUTS, THE NEXT FOUR FOR THE STATUS QUO**
C**       MACHINECAPACITY, THE NEXT FOUR FOR THE IST**
C**     YEAR AND 2ND YEAR CHALLENGERS, AND THE LAST THIS**
C**     YEAR'S AGV CAPACITY**
C**  14.THE MACHINE VALUES FOR ALL INDIVIDUAL MACHINES**
C**      IN YEAR TWO.**
      READ(5,*)(TDETE(M),M=1,KI)
      READ(5,*)(DIDL(M),M=1,KI)
      READ(5,*)(DDL(M),M=1,KI)
      READ(5,*)(DMIS(M),M=1,KI)
      READ(5,*)(DMANT(M),M=1,KI)
      READ(5,*)(TOBS(M),M=1,KI)
      READ(5,*)(PB2(I),I=1,IPA)
      READ(5,*)(OIDL(M),M=1,KI)
      READ(5,*)(ODL(M),M=1,KI)
      READ(5,*)(OMIS(M),M=1,KI)
      READ(5,*)(OMANT(M),M=1,KI)
      DO 422 I=1,IPA
      KK=PB2(I)
      DO 422 J=1,KK
      READ(5,*)P2(I,J),XLL2(I,J),XUL2(I,J)
```

```
  422 CONTINUE
      READ(5,*)IDLC2,DLC2,MISC2,MANTC2
      I3=4+MC+NNEW
      DO 373 M=1,I3
 373  READ(5,*) TRH2(M)
      J1=JT+1
      DO 503 N4=JT,J1
      DO 104 N2=1,NICUM
      N3=N2+1
 104  READ(5,*)MVALUE(N4,N3)
      DO 102 N5=1,NNEW
      N6=N5+MC
      READ(5,*)MVALUE(N4,N6)
 102   CONTINUE
 503  CONTINUE
C
C    THE FOLLOWING UDATES THE PARAMETERS FOR YEAR TWO
C
      DO 437 J=1,NNEW
 437  MCH(J)=MC+J
C
      DO 721 I=1,IPA
      IK=K(I)
      DO 721 J=1,IK
      DO 721 M=1,KI
      IF(TIMC(I,J,M).EQ.999)GOTO 721
      TIMC(I,J,M)=TIMC(I,J,M)*TDETE(M)
721      CONTINUE
      DO 722 M=1,KI
      TIDL(M)=TIDL(M)*DIDL(M)
      TDL(M)=TDL(M)*DDL(M)
      TMIS(M)=TMIS(M)*DMIS(M)
 722  TMANT(M)=TMANT(M)*DMANT(M)
      DO 724 I=1,IPA
      KK=PB2(I)
      DO 723 J=1,KK
      P(I,J)=P2(I,J)
      XUL(I,J)=XUL2(I,J)
      XLL(I,J)=XLL2(I,J)
723   CONTINUE
724   CONTINUE
      X$IDL=X$IDL*IDLC2
      X$DL=X$DL*DLC2
      X$MIS=X$MIS*MISC2
      X$MANT=X$MANT*MANTC2
      DO 725 M=1,13
  725 TRH(M)=TRH2(M)
      IB=MC+2
      IA=MC+1
```

```
      DO 726 I=1,IPA
      KK=K(I)
      DO 726 J=1,KK
      DO 726 M=IA,IB
      N=M+2
      IF(TIMC(I,J,M).EQ.999)GOTO 762
```

```
      TIMC(I,J,N)=TIMC(I,J,M)*TOBS(M)/TDETE(M)
      GOTO 726
762   TIMC(I,J,N)=999.
 726        CONTINUE
      DO 727 M=IA,IB
      N=M+2
      TIDL(N)=TIDL(M)*OIDL(M)/DIDL(M)
      TDL(N)=TDL(M)*ODL(M)/DDL(M)
      TMIS(N)=TMIS(M)*OMIS(M)/DMIS(M)
      TMANT(N)=TMANT(M)*OMANT(M)/DMANT(M)
  727 CONTINUE
C     T=2
C
C   THE FOLLOWING COMPUTES THE MAXIMUM OPERATING PROFIT FOR THE
C     STATUS QUO CONFIGURATION IN YEAR TWO
      NDE=0
      NCH=0
      I=1
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2005
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
 2005 CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
      OPPF(2,1)=OPT
C
C    THE FOLLOWING COMPUTES THE ONE-DEFENDER/ONE-CHALLENGER CASE
      NDE=1
      NCH=1
       DO 514 J=1,NICUM
      DO 514 M=1,NNEW
      I=I+1
       IDE(1)=MDE(J)
      ICH(1)=MCH(M)
      IRB(1)=MCH(M)
       ITORE(1)=MDE(J)
C
```

```
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
       IF(INFEA.EQ.0)GOTO 2006
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
2006  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
      OPPF(2,I)=OPT
  514 CONTINUE
C
C
C   THE FOLLOWING COMPUTES THE TWO-DEFENDER/ONE CHALLENGER CASE
C
```

```
C
      NDE=2
      NCH=1
        DO 511 M=1,NNEW
        IDE(1)=MDE(1)
       IDE(2)=MDE(2)
       ICH(1)=MCH(M)
        IRB(1)=MCH(M)
       IRB(2)=99
       ITORE(1)=MDE(1)
C
       I=I+1
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
       IF(INFEA.EQ.0)GOTO 2007
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
C
2007  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
      OPPF(2,I)=OPT
  511 CONTINUE
C
C
C
C   THE FOLLOWING COMPUTES THE TWO-DEFENDER/TWO CHALLENTER CASE
C
      NDE=2
      NCH=2
```

```
      DO 434 MM=1,NNEW
      ITWO(1)=MM
      JMM=MM+1
      IF(MM.EQ.4)GOTO 434
       DO 454 IKN=JMM,NNEW
      ITWO(2)=IKN
      NT=MM+NCH
       IF(NT.EQ.IKN)GOTO 454
      DO 464 KK=1,NICUM
       IONE(KK)=KK
      IDE(KK)=MDE(IONE(KK))
      ICH(KK)=MCH(ITWO(KK))
      IRB(KK)=MCH(ITWO(KK))
 464  ITORE(KK)=MDE(IONE(KK))
      I=I+1
C
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2008
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
2008  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
HOLD     DATA     D1  08/04/83  4:52 101__D     F 80    1823 RECS    VA TECH    PRINTED 08/04/83 05:06    PAGE 011

     *XMIS,XMANT,INFEA)
      OPPF(2,I)=OPT
  454  CONTINUE
 434  CONTINUE
C
C     THIS IS WHERE THE THIRD YEAR STARTS
C
C
C*********************************************************************
C**     THIS SECTION CALCULATES THE MAXIMUM OPERATING PROFIT
C**     FOR ALL FMS CONFIGURATIONS IN YEAR TWO
C**   THE REQUIREMENT OF DATA AND THERE ORDER OF ENTRY IS
C** IDENTICAL TO THAT OF YEAR TWO WITH THE FOLLOWING
C**    EXCEPTION: 1.THE MACHINE CAPACITY OF THE NEW CHALLENGERS
C**                 IS INPUT RIGHT AFTER YEAR TWO'S CHALLENGERS
C**              2.THE MACHINE VALUES OF THE NEW CHALLENGERS IS INPUT
C**                     RIGHT AFTER YEAR TWO'S CHALLENGERS
C*****************************************
      NNEW=4
         W=W*1.1
      WRITE(6,666)
666    FORMAT(25X,'FMS CONFIGURATIONS IN YEAR THREE')
C
```

```
C
C
      NCON(2)=I
      JT=3
      KI=MC+NNEW
      NNEW=(3*NNEW)/2
      READ(5,*)(TDETE(M),M=1,KI)
      READ(5,*)(DIDL(M),M=1,KI)
      READ(5,*)(DDL(M),M=1,KI)
      READ(5,*)(DMIS(M),M=1,KI)
      READ(5,*)(DMANT(M),M=1,KI)
      READ(5,*)(TOBS(M),M=1,KI)
      READ(5,*)(PB3(I),I=1,IPA)
      READ(5,*)(OIDL(M),M=1,KI)
      READ(5,*)(ODL(M),M=1,KI)
      READ(5,*)(OMIS(M),M=1,KI)
      READ(5,*)(OMANT(M),M=1,KI)
      DO 822 I=1,IPA
      KK=PB3(I)
      DO 822 J=1,KK
      READ(5,*)P3(I,J),XLL3(I,J),XUL3(I,J)
  822 CONTINUE
      READ(5,*)IDLC3,DLC3,MISC3,MANTC3
C     WRITE(6,*)IDLC3,DLC3,MISC3,MANTC3
      J3=NNEW+4+MC
      DO 257 M=1,J3
257    READ(5,*)TRH3(M)
      DO 731 I=1,IPA
      IK=K(I)
      DO 731 J=1,IK
      DO 731 M=1,KI
      IF(TIMC(I,J,M).EQ.999)GOTO 731
```

```
      TIMC(I,J,M)=TIMC(I,J,M)*TDETE(M)
 731    CONTINUE
C
      DO 732 M=1,KI
       TIDL(M)=TIDL(M)*DIDL(M)
      TDL(M)=TDL(M)*DDL(M)
       TMIS(M)=TMIS(M)*DMIS(M)
 732  TMANT(M)=TMANT(M)*DMANT(M)
       DO 734 I=1,IPA
      KK=PB3(I)
      DO 733 J=1,KK
       P(I,J)=P3(I,J)
      XUL(I,J)=XUL3(I,J)
      XLL(I,J)=XLL3(I,J)
733     CONTINUE
```

```
734   CONTINUE
C
C
C
      X$IDL=X$IDL*IDLC3
      X$DL=X$DL*DLC3
      X$MIS=X$MIS*MISC3
      X$MANT=X$MANT*MANTC3
      KI=4+MC+NNEW
      DO 735 M=1,KI
  735 TRH(M)=TRH3(M)
C
C
      J1=JT+1
      DO 303 N4=JT,J1
      DO 304 N2=1,NICUM
      N3=N2+1
  304 READ(5,*)MVALUE(N4,N3)
      DO 302 N5=1,NNEW
      N6=N5+MC
      READ(5,*) MVALUE(N4,N6)
  302 CONTINUE
 303  CONTINUE
C     WRITE(6,*)MVALUE(4,9)
      DO 417 J=1,NNEW
417    MCH(J)=MC+J
C
C     THE FOLLOWING UPDATES THE PARAMETERS FOR YEAR THREE
C
       IB =MC+4
      IA=MC+3
       DO 736 I=1,IPA
       KK=K(I)
       DO 736 J=1,KK
      DO 736 M=IA,IB
      N=M+2
      IF(TIMC(I,J,M).EQ.999)GOTO 763
      TIMC(I,J,N)=TIMC(I,J,M)*TOBS(M)/TDETE(M)
      GOTO 736
763   TIMC(I,J,N)=999.
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 736   CONTINUE
      DO 737 M=IA,IB
       N=M+2
        TIDL(N)=TIDL(M)*OIDL(M)/DIDL(M)
       TDL(N)=TDL(M)*ODL(M)/DDL(M)
      TMIS(N)=TMIS(M)*OMIS(M)/DMIS(M)
```

```
      TMANT(N)=TMANT(M)*OMANT(M)/DMANT(M)
 737  CONTINUE
C
C
C    THE FOLLOWING COMPUTES THE MAXIMUM OPERATING PROFIT
C       FOR THE STATUS QUO CONFIGURATION IN YEAR THREE
C     T=3
C
      I=1
      NDE=0
      NCH=0
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2101
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
2101  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
        OPPF(3,1)=OPT
C
C
C     THE FOLLOWING COMPUTES THE ONE-DEFENDER/ONE CHALLENGER
C     CASE
      NDE=1
      NCH=1
      DO 145 J=1,NICUM
      DO 145 M=1,NNEW
      I=I+1
      IDE(1)=MDE(J)
      ICH(1)=MCH(M)
      IRB(1)=MCH(M)
      ITORE(1)=MDE(J)
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2009
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
C
2009  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
 145    OPPF(3,I)=OPT
C       THE FOLLOWING COMPUTES THE TWO-DEFENDER/TWO-CHALLENGERCASE
      NDE=2
      NCH=1
      DO 146 M=1,NNEW
```

```
      IDE(1)=MDE(1)
      IDE(2)=MDE(2)
      ICH(1)=MCH(M)
      IRB(2)=99
      ITORE(1)=MDE(1)
C
      I=I+1
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2010
      CALL OPTIMU(A,BH,OBJ,NC2,IDS,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,PO
     *,PB,XOPT,IPA,MC,ID)
C
2010  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
      OPPF(3,I)=OPT
  146 CONTINUE
C
C    THE FOLLOWING COMPUTES THE TWO-DEFENDER/TWO-CHALLENGER CASE
C
      NDE=2
      NCH=2
      DO 334 MM=1,NNEW
      ITWO(1)=MM
      JMM=MM+1
      IF(MM.EQ.6)GOTO 334
      DO 365 IKN=JMM,NNEW
      ITWO(2)=IKN
      NT=MM+NCH
      INT=NCH*2+MM
      IF(NT.EQ.IKN.OR.IKN.EQ.INT)GOTO 365
      DO 364 KK=1,NICUM
      IONE(KK)=KK
      IDE(KK)=MDE(IONE(KK))
      ICH(KK)=MCH(ITWO(KK))
      IRB(KK)=MCH(ITWO(KK))
  364 ITORE(KK)=MDE(IONE(KK))
      I=I+1
C
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 2011
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
2011  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
```

```
     *XMIS,XMANT,INFEA)
      OPPF(3,I)=OPT
C
C
 365  CONTINUE
334   CONTINUE
```

```
C
C
C
C     THIS IS WHERE THE FOURTH YEAR STARTS
C*********************************************
C**   THIS SECTION COMPUTES THE MAXIMUM OPERATING
C**     FOR ALL FMS CONFIGURATIONS IN YEAR THREE
C**   THE DATA REQUIREMENT AND ORDER OF ENTRY ARE
C** ARE SIMILARLY APPROACHED AS IN YEAR FOUR
C**********************************************
C
C
C     T=4
      WRITE(6,766)
766     FORMAT(25X,'FMS CONFIGURATIONS IN YEAR FOURTH')
      NCON(3)=I
      JT=4
       W=W*1.1
      KI=MC+NNEW
      NNEW=4*(NNEW/3)
      READ(5,*)(TDETE(M),M=1,KI)
      READ(5,*)(DIDL(M),M=1,KI)
      READ(5,*)(DDL(M),M=1,KI)
      READ(5,*)(DMIS(M),M=1,KI)
      READ(5,*)(DMANT(M),M=1,KI)
      READ(5,*)(TOBS(M),M=1,KI)
      READ(5,*)(PB4(I),I=1,IPA)
C     WRITE(6,*)(PB4(I),I=1,IPA)
      READ(5,*)(OIDL(M),M=1,KI)
      READ(5,*)(ODL(M),M=1,KI)
      READ(5,*)(OMIS(M),M=1,KI)
      READ(5,*)(OMANT(M),M=1,KI)
      DO 802 I=1,IPA
      KK=PB4(I)
      DO 802 J=1,KK
      READ(5,*)P4(I,J),XLL4(I,J),XUL4(I,J)
  802 CONTINUE
      READ(5,*)IDLC4,DLC4,MISC4,MANTC4
C     WRITE(6,*)IDLC4,DLC4,MISC4,MANTC4
      J4=NNEW+4+MC
```

```
      DO 207 M=1,J4
207    READ(5,*)TRH4(M)
      DO 934 I=1,IPA
      IK=K(I)
      DO 934 J=1,IK
      DO 934 M=1,KI
      IF(TIMC(I,J,M).EQ.999)GOTO 934
      TIMC(I,J,M)=TIMC(I,J,M)*TDETE(M)
 934    CONTINUE
C
      DO 932 M=1,KI
       TIDL(M)=TIDL(M)*DIDL(M)
      TDL(M)=TDL(M)*DDL(M)
       TMIS(M)=TMIS(M)*DMIS(M)
 932  TMANT(M)=TMANT(M)*DMANT(M)
```

```
       DO 784 I=1,IPA
      KK=PB4(I)
      DO 783 J=1,KK
       P(I,J)=P4(I,J)
      XUL(I,J)=XUL4(I,J)
      XLL(I,J)=XLL4(I,J)
783     CONTINUE
784   CONTINUE
C
C
C
      X$IDL=X$IDL*IDLC4
      X$DL=X$DL*DLC4
      X$MIS=X$MIS*MISC4
      X$MANT=X$MANT*MANTC4
      KI=4+MC+NNEW
      DO 785 M=1,KI
  735 TRH(M)=TRH4(M)
C
C
      J1=JT+1
      DO 383 N4=JT,J1
      DO 384 N2=1,NICUM
      N3=N2+1
  334 READ(5,*)MVALUE(N4,N3)
      DO 382 N5=1,NNEW
      N6=N5+MC
      READ(5,*) MVALUE(N4,N6)
  382 CONTINUE
 383  CONTINUE
C     WRITE(6,*)MVALUE(5,9)
```

```
      DO 3000 J=1,NNEW
3000   MCH(J)=MC+J
        IB =MC+6
      IA=MC+5
       DO 836 I=1,IPA
       KK=K(I)
       DO 836 J=1,KK
      DO 836 M=IA,IB
      N=M+2
      IF(TIMC(I,J,M).EQ.999)GOTO 863
      TIMC(I,J,N)=TIMC(I,J,M)*TOBS(M)/TDETE(M)
      GOTO 836
863   TIMC(I,J,N)=999.
 836   CONTINUE
      DO 837 M=IA,IB
       N=M+2
        TIDL(N)=TIDL(M)*OIDL(M)/DIDL(M)
       TDL(N)=TDL(M)*ODL(M)/DDL(M)
      TMIS(N)=TMIS(M)*OMIS(M)/DMIS(M)
      TMANT(N)=TMANT(M)*OMANT(M)/DMANT(M)
 837  CONTINUE
C
C
C     T=4
```

```
C
C      THE FOLLOWING COMPUTES THE MAXIMUM OPERATING PROFIT FOR
C      THE STATUS QUO CONFIGURATION FOR YEAR FOUR
C
      I=1
      NDE=0
      NCH=0
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
       IF(INFEA.EQ.0)GOTO 3101
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
3101  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
        OPPF(4,1)=OPT
C
C
      NDE=1
C    THE FOLLOWING COMPUTES THE ONE-DEFENDER/ONE-CHALLENGER CASE
C
```

```
      NCH=1
      DO 645 J=1,NICUM
      DO 645 M=1,NNEW
      I=I+1
      IDE(1)=MDE(J)
      ICH(1)=MCH(M)
      IRB(1)=MCH(M)
      ITORE(1)=MDE(J)
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 3009
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
C
3009  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
 645    OPPF(4,I)=OPT
C
C    THE FOLLOWING COMPUTES THE TWO-DEFENDER/ONE-CHALLENGER CASE
C
      NDE=2
      NCH=1
      DO 646 M=1,NNEW
      IDE(1)=MDE(1)
      IDE(2)=MDE(2)
      ICH(1)=MCH(M)
      IRB(2)=99
      ITORE(1)=MDE(1)
      I=I+1
C
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
```

```
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 3010
      CALL OPTIMU(A,BH,OBJ,NC2,IDS,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,PO
     *,PB,XOPT,IPA,MC,ID)
C
3010  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
      OPPF(4,I)=OPT
  646 CONTINUE
C     THE FOLLOWING COMPUTES THE TWO-DEFENDER/TWO-CHALLENGER CASE
C
C
```

```
      NDE=2
      NCH=2
       DO 674 MM=1,NNEW
      ITWO(1)=MM
      JMM=MM+1
      IF(MM.EQ.8)GOTO 674
      DO 465 IKN=JMM,NNEW
      ITWO(2)=IKN
      NT=MM+NCH
      INT=NCH*2+MM
      KNT=NCH*3+MM
      IF(IKN.EQ.KNT)GOTO 465
      IF(NT.EQ.IKN.OR.IKN.EQ.INT)GOTO 465
      DO 874 KK=1,NICUM
      IONE(KK)=KK
      IDE(KK)=MDE(IONE(KK))
      ICH(KK)=MCH(ITWO(KK))
      IRB(KK)=MCH(ITWO(KK))
 874  ITORE(KK)=MDE(IONE(KK))
      I=I+1
C
      CALL MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,XMANT,
     *XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,I,ELEM,JT,IDE,NICUM,NNEW)
      CALL SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALPHA,IID
     *,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      IF(INFEA.EQ.0)GOTO 3011
      CALL OPTIMU(A,BH,OBJ,NC2,ID,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P,POB
     *,PB,XOPT,IPA,MC,ID)
3011  CALL WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL,XIDL,
     *XMIS,XMANT,INFEA)
      OPPF(4,I)=OPT
C
C
 465  CONTINUE
 674  CONTINUE
      NCON(4)=I
C
C
C*******************************************
C****       ENTER THE TIME VALUE OF MONEY ****
C
```

```
C
      TAX=.5
       READ(5,*)RATE
C
C     AFTER THE OPERATING PROFIT FOR EACH FMS CONFIGURATION
C      IS COMPUTED, THE FOLLOWING DETERMINES THE OPTIMAL FMS
```

```
C        CONFIGURATION SEQUENCE. THAT IS, THE OPTIMAL REPLACEMENT
C           POLICY
C*****************************************************************
C
C    ICON DENOTES THE NUMBER OF CONFIGURATIONS IN YEAR I
      I1=NCON(1)
      I2=NCON(2)
      I3=NCON(3)
      I4=NCON(4)
C
C       THE FOLLOWING COMPUTES THE OPTIMAL RETURN VALUES FOR
C        ALL FMS CONFIGURATIONS IN YEAR ONE
C
      NT=1
      DO 471 I=1,I1
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
 471   F(1,I)=(OPPF(1,I)-(OPPF(1,I)-DEP(1,I))*TAX-DEP(1,I)-CCOST(1,I))*(
     *1+RATE)**3
C       THE FOLLOWING COMPUTES THE OPTIMAL RETURN VALUES FOR
C         ALL FMS CONFIGURATIONS IN YEAR TWO
       NT=2
      DO 472 I=1,I2
      IH=0
      DO 474 N=1,I1
      DO 473 J=1,2
      IF(ELEM(2,I,J).EQ.ELEM(1,N,J))IH=IH+1
 473   CONTINUE
      IF(IH.EQ.2)GOTO 475
      IH=0
 474   CONTINUE
       DO 476 J=1,2
      IF(ELEM(2,I,J).EQ.6.OR.ELEM(2,I,J).EQ.7)GOTO 477
 476   CONTINUE
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(2,I)=F(1,1)+(OPPF(2,I)-(OPPF(2,I)-DEP(2,I))*TAX-DEP(2,I)-CCOST(2
     *,I))*(1+RATE)**2
      TID(2,I)=1.
      GOTO 472
 475  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(2,I)=F(1,N)+(OPPF(2,I)-(OPPF(2,I)-DEP(2,I))*TAX-DEP(2,I)-CCOST(2
     *,I))*(1+RATE)**2
      TID(2,I)=N
      GOTO 472
  477 IF(ELEM(2,I,J).EQ.6)GOTO 480
      IF(F(1,3).GT.F(1,5))GOTO 479
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(2,I)=F(1,5)+(OPPF(2,I)-(OPPF(2,I)-DEP(2,I))*TAX-DEP(2,I)-CCOST(2
     *,I))*(1+RATE)**2
C
```

```
      TID(2,I)=5
      GOTO 472
  479 CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(2,I)=F(1,3)+(OPPF(2,I)-(OPPF(2,I)-DEP(2,I))*TAX-DEP(2,I)-CCOST(2
     *,I))*(1+RATE)**2
      TID(2,I)=3
      GOTO 472
  480 IF(F(1,2).GT.F(1,4))GOTO 481
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(2,I)=F(1,4)+(OPPF(2,I)-(OPPF(2,I)-DEP(2,I))*TAX-DEP(2,I)-CCOST(2
     *,I))*(1+RATE)**2
      TID(2,I)=4
      GOTO 472
  481 CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(2,I)=F(1,2)+(OPPF(2,I)-(OPPF(2,I)-DEP(2,I))*TAX-DEP(2,I)-CCOST(2
     *,I))*(1+RATE)**2
      TID(2,J)=2
      GOTO 472
  472 CONTINUE
C     THE FOLLOWING DETERMINES THE OPTIMAL RETURN FUNCTION FOR
C       ALL FMS CONFIGURATIONS IN YEAR THREE
C
      NT=3
       DO 482 I=1,13
      IH=0
      DO 484 N=1,12
      DO 483 J=1,2
      IF(ELEM(3,I,J).EQ.ELEM(2,N,J))IH=IH+1
  483 CONTINUE
      IF(IH.EQ.2) GOTO 485
      IH=0
  484 CONTINUE
      DO 486 J=1,2
      IF(ELEM(3,I,J).EQ.6)GOTO 491
      IF(ELEM(3,I,J).EQ.7)GOTO 492
      IF(ELEM(3,I,J).EQ.8)GOTO 493
      IF(ELEM(3,I,J).EQ.9)GOTO 494
  486 CONTINUE
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,1)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
      TID(3,I)=1
      GOTO 482
  485 CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,N)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
       TID(3,I)=N
      GOTO 482
  491 IF(F(2,2).GT.F(2,6))GOTO 496
```

```
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,6)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
      TID(3,I)=6
      GOTO 482
 496  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
```

```
      F(3,I)=F(2,2)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
      TID(3,I)=2
      GOTO 482
 492  IF(F(2,3).GT.F(2,7))GOTO 497
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,7)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
      TID(3,I)=7
      GOTO 482
 497  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,3)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
      TID(3,I)=3
      GOTO 482
 493   IF(F(2,4).GT.F(2,8))GOTO 498
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,8)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
       TID(3,I)=8
      GOTO 482
 498  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,4)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
      TID(3,I)=4
      GOTO 482
 494  IF(F(2,5).GT.F(2,9))GOTO 499
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,9)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
       TID(3,I)=9
      GOTO 482
 499  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(3,I)=F(2,5)+(OPPF(3,I)-(OPPF(3,I)-DEP(3,I))*TAX-DEP(3,I)-CCOST(3
     *,I))*(1+RATE)**1
      TID(3,I)=5
 482  CONTINUE
C
C    THE FOLLOWING COMPUTES THE OPTIMAL RETURN FOR ALL FMS
C     CONFIGURATIONS IN YEAR
```

```
      NT=4
       DO 882 I=1,14
      IH=0
      DO 884 N=1,13
      DO 883 J=1,2
      IF(ELEM(4,I,J).EQ.ELEM(3,N,J))IH=IH+1
 883  CONTINUE
      IF(IH.EQ.2) GOTO 885
      IH=0
 884  CONTINUE
      DO 886 J=1,2
      IF(ELEM(4,I,J).EQ.6)GOTO 891
      IF(ELEM(4,I,J).EQ.7)GOTO 892
      IF(ELEM(4,I,J).EQ.8)GOTO 893
      IF(ELEM(4,I,J).EQ.9)GOTO 894
```

```
      IF(ELEM(4,I,J).EQ.10)GOTO 895
      IF(ELEM(4,I,J).EQ.11)GOTO 8906
 886  CONTINUE
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,1)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
      TID(4,I)=1
      GOTO 882
 885  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,N)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
       TID(4,I)=N
      GOTO 882
 891  IF(F(3,2).GT.F(3,8))GOTO 896
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,8)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
      TID(4,I)=8
      GOTO 882
 896  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,2)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
      TID(4,I)=2
      GOTO 882
 892  IF(F(3,3).GT.F(3,9))GOTO 897
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,9)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
      TID(4,I)=9
      GOTO 882
 897  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
```

```
      F(4,I)=F(3,3)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
      TID(4,I)=3
      GOTO 882
 893   IF(F(3,4).GT.F(3,10))GOTO 898
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,10)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(
     *4,I))*(1+RATE)**1
        TID(4,I)=10
      GOTO 882
 898  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,4)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
      TID(4,I)=4
      GOTO 882
 894  IF(F(3,5).GT.F(3,11))GOTO 899
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,11)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(
     *4,I))*(1+RATE)**1
        TID(4,I)=11
      GOTO 882
 899  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,5)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
```

```
      TID(4,I)=5
      GOTO 882
 895   IF(F(3,6).GT.F(3,12))GOTO 818
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,12)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(
     *4,I))*(1+RATE)**1
        TID(4,I)=12
      GOTO 882
 818  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,6)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
     *,I))*(1+RATE)**1
      TID(4,I)=6
      GOTO 882
8906  IF(F(3,7).GT.F(3,13))GOTO 819
      CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,13)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(
     *4,I))*(1+RATE)**1
        TID(4,I)=13
C
      GOTO 882
 819  CALL CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      F(4,I)=F(3,7)+(OPPF(4,I)-(OPPF(4,I)-DEP(4,I))*TAX-DEP(4,I)-CCOST(4
```

```
     *,I))*(1+RATE)**1
      TID(4,I)=7
 882  CONTINUE
C
C
C
C
      WRITE(6,8656)
 8656 FORMAT(///,25X,'THE OPTIMAL RETURN VALUES (F-VALUES) FOR ALL CONFI
     *GURATIONS:')
      DO 2222 I=1,4
      IHJ=NCON(I)
2222   WRITE (6,*)(F(I,J),J=1,IHJ)
C
C
C
C       THE FOLLOWING COMPUTES THE MAXIMUM OPTIMAL RETURN
C         VALUE FOR THE FINAL PERIOD. THEN THE OPTIMAL
C          REPLACEMENT SEQUENCE IS TRACED
      NY=4
      CALL DPOPT(F,TID,NCON,NY,NON)
      WRITE(6,9001)
9001   FORMAT(1H1,23X,'YEAR',8X,'CONF.',6X,'F-VALUES')
      DO 8001 I=1,NY
8001  WRITE(6,7001)I,NON(I),F(I,NON(I))
 7001 FORMAT(25X,I1,10X,I3,6X,F12.2)
C
C
        CONTINUE
      STOP
      END
C
C
HOLD     DATA     D1  08/04/83  4:52 101__D     F 80    1823 RECS    VA TECH    PRINTED 08/04/83 05:06    PAGE 024

C*******************************************************************
C**   THIS SUBROUTINE COMPUTES THE MAXIMUM OPTIMAL RETURN VALUE    *
C**   FOR ALL FMS CONFIGUATION                                     *
C**   AT THE END OF THE PLANNING HORIZON. THE OPTIMAL REPLACEMENT *
C**   POLICY IS THEN TRACED                                        *
C********************************************************************
      SUBROUTINE DPOPT(F,TID,NCON,NY,NON)
      DIMENSION F(6,100),TID(6,100),NCON(6),NON(6)
      MAXIM=F(NY,1)
      IY=NCON(NY)
      ICON=1
       DO 1 I=2,IY
      IF(MAXIM.GT.F(NY,I))GOTO 1
```

```
      MAXIM=F(NY,I)
      ICON=I
1     CONTINUE
       WRITE(6,*)MAXIM,ICON,NY
      NON(NY)=ICON
      NY=NY-1
      M=ICON
      DO 2 J=1,NY
      K=NY-J+2
      N=K-1
      NON(N)=FID(K,M)
      M=NON(N)
 2    CONTINUE
      NY=NY+1
      RETURN
      END
C
C
C
C    *****************************************************************
C    ***     THIS SUBROUTINE PRINTS OUT THE RESULTS OF EACH          ***
C    ***        FMS CONFIGURATION :                                  ***
C    ***             PARTS ASSIGNMENT, OPTIMAL OPERATING PROFIT      ***
C    ***             PRICE OF EACH PART TYPE ...ETC.                 ***
C    *****************************************************************
C
C
C
      SUBROUTINE WRT(ID,NC2,IPA,K,MC,W,ALPHA,T,DD,A,OPT,OBJ,XOPT,IID,XDL
C
     *,XIDL,XMIS,XMANT,INFEA)
      DIMENSION K(10),T(10,10,10),DD(10,10),A(150,150),OBJ(150)
      DIMENSION XOPT(150),IID(10,10,10,10),XDL(20)
      DIMENSION XIDL(20),XMIS(20),XMANT(20)
C
C
C
C
C
      IF(OPT.EQ.0)GOTO 523
      IF(INFEA.EQ.0)GOTO 523
C     WRITE(6,801)ID
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C801  FORMAT(1H1,25X,'THE NUMBER OF VARIABLES IS',2X,I3,////)
C     WRITE(6,802)NC2
C 802 FORMAT(25X,'THE NUMBER OF CONSTRAINTS IS',2X,I3,///)
C     WRITE(6,201)IPA
C201  FORMAT(1H1,15X,'THE TOTAL NUMBER OF PART TYPES IS : ',I3)
```

```
C      WRITE(6,203)(K(IP),IP=1,IPA)
C      WRITE (6,204)MC
C204   FORMAT(//,15X,'THE TOTAL NUMBER OF MACHINE STATIONS (INCLUDING LOA
C     *D AND UNLOAD STATION IS : ', 2X,I2)
C      WRITE (6,205)W
C205   FORMAT(//,15X,'THE MATERIAL HANDLING COST(PER UNIT FOOT TRAVELLED
C     *THE AGV) IS : ',2X,F5.2,1X,'DOLLAR')
C      WRITE(6,206)ALPHA
C206    FORMAT(//,15X,'THE UTILIZATION RATE OF THE AGV IS : ',2X,F5.2)
C 203  FORMAT(//,15X,'TOTAL OPERATIONS FOR EACH PART TYPE RESPECTIVELY IS
C     * :',2X,10(I2,2X))
C      WRITE (6,208)
 208   FORMAT(1H1,15X,'THE OPERATION TIMES PER MACHINE TYPE PER PRT IS AS
      *FOLLOWING ,STARTING WITH THE FIRST PART TYPE :',//)
       DO 217 I=1,IPA
       IKK=K(I)
       DO 207 IK=1,IKK
 207   WRITE (6,*)(T(I,IK,M),M=1,MC)
       WRITE(6,285)
 285   FORMAT(//)
 217   CONTINUE
C      WRITE(6,209)
C 209  FORMAT(1H1,15X,'THE DISTANCE MATRIX FOR THE LAYOUT IS AS FOLLOW :
C     *',//)
C      WRITE(6,210)(I,I=1,MC)
C210   FORMAT(25X,I2,10(5X,I4),//)
C      DO 211 I=1,MC
C      WRITE(6,212)I,(DD(I,J),J=1,MC)
C212   FORMAT(20X,I2,10(3X,F6.2),//)
C211   CONTINUE
       WRITE (6,286)
  286  FORMAT(1H1,25X,'THE UNIT COST OF RESPECTIVE INPUTS PER MACHINE ARE
      * :',//)
       WRITE(6,287)
 287   FORMAT (15X,'DIRECT LABOR',5X,'INDIRECT LABOR',5X,'MISCELLANEOUS',
      *5X,'MAINTENANCE',//)
       DO 214 I=1,MC
       WRITE(6,213)I,XDL(I),XIDL(I),XMIS(I),XMANT(I)
 213   FORMAT(10X,I2,10(10X,F5.2),//)
 214   CONTINUE
C      WRITE(6,487)
C487   FORMAT(1H1,35X,'THE FOLLOWING IS THE A-MATRIX',///)
C      DO 223 I=1,NC2
C223   WRITE(6,232)(A(I,J),J=1,ID)
C232   FORMAT(2X,30(F3.0,1X),/,2X,30(F3.0,1X),/,2X,30(F3.0,1X),//)
       WRITE(6,876)
 876   FORMAT(1H1,35X,'THE OPTIMUM IS')
       WRITE(6,4321)OPT
4321    FORMAT(39X,F12.2)
```

```
      WRITE(6,878)
```

```
  873 FORMAT(///,25X,'THE ASSIGNMENTS OF PARTS ARE AS FOLLOW : ',//)
      WRITE(6,131)
  131 FORMAT(23X,'VAR',4X,'P',4X,'K',4X,'M',4X,'S',6X,'OBJ.',4X,'Y(P,K,M
     *,S)')
       DO 531 IX=1,ID
      DO 532 I=1,IPA
      IKK=K(I)
      DO 532 J=1,IKK
      DO 532 M=1,MC
      DO 532 IM=1,MC
      IF(IX.NE.IID(I,J,M,IM))GOTO 532
      WRITE(6,5312)IX,I,J,M,IM,OBJ(IX),XOPT(IX)
 5312  FORMAT(23X,I3,3X,I2,3X,I2,3X,I2,3X,I2,3X,F8.2,3X,F8.2)
       GO TO 531
  532 CONTINUE
  531  CONTINUE
      GOTO 542
  523 OPT=0.
       WRITE(6,513)
  513    FORMAT(25X,' THIS CONFIGURATION IS INFEASIBLE ')
       WRITE(6,208)
      DO 917 I=1,IPA
      IKK=K(I)
      DO 907 IK=1,IKK
  907 WRITE(6,*)(T(I,IK,M),M=1,MC)
      WRITE(6,285)
  917  CONTINUE
  542    CONTINUE
      RETURN
      END
C
C
C
C    ****************************************************************
C    ***       THIS SUBROUTINE CALCULATES THE CAPITALIZED COST       ***
C    ***         OF EACH FMS CONFIGURATION                           ***
C    ****************************************************************
C
C
      SUBROUTINE CAPCOS(NT,I,DEP,MVALUE,TAX,RATE,ELEM,CCOST)
      DIMENSION DEP(6,100),MVALUE(6,100),ELEM(6,100,2),CCOST(6,100)
      MVALUE(NT,99)=0
      MT=NT+1
      MVALUE(MT,99)=0
      DEP(NT,I)=MVALUE(NT,ELEM(NT,I,1))-MVALUE(MT,ELEM(NT,I,1))+MVALUE(N
```

```
     *T,ELEM(NT,I,2))-MVALUE(MT,ELEM(NT,I,2))
      CCOST(NT,I)=(MVALUE(NT,ELEM(NT,I,1))+MVALUE(NT,ELEM(NT,I,2)))*RATE
      RETURN
      END
C
C
C
C
C
C     ****************************************************************
```

```
C     ***      THIS SUBROUTINE ESTABLISHES THE MAJOR PARAMETERS       ***
C     ***         OF A GIVEN FMS CONFIGURATION                        ***
C     ****************************************************************
C
C
C
      SUBROUTINE MCONF(IPA,K,MC,NCH,ICH,IRB,NDE,ITORE,T,TIMC,XIDL,XMIS,X
     *MANT,XDL,TIDL,TDL,TMIS,TMANT,RH,TRH,NI,ELEM,JT,IDE,NICUM,NNEW)
C
C
      DIMENSION INDE(100),K(10),ICH(20),IRB(20),IDE(20)
      DIMENSION ITORE(20),T(10,10,10),TIMC(10,10,20),XMIS(20)
      DIMENSION XMANT(20),XDL(20),TIDL(20),TDL(20),TMIS(20)
      DIMENSION TMANT(20),RH(20),TRH(20),XIDL(20),ELEM(6,100,2)
C
      WRITE(6,*)NCH,NDE,ITORE(1),ICH(1)
      DO 222 M=1,MC
 222  INDE(M)=M
      IF(NCH.EQ.0)GOTO 282
      IF(NCH.LT.NDE)GOTO 275
      DO 272 I=1,NCH
 272  INDE(ITORE(I))=ICH(I)
      GOTO 282
 275  DO 273 I=1,NCH
  273 INDE(ITORE(I))=ICH(I)
      DO 274 J=1,NDE
      IF(IRB(J).NE.99)GOTO 274
      INDE(IDE(J))=99
 274  CONTINUE
 282  DO 292 I=1,IPA
      IK=K(I)
      DO 292 J=1,IK
      DO 292 M=1,MC
      IF(INDE(M).EQ.99)GOTO 262
      T(I,J,M)=TIMC(I,J,INDE(M))
      GOTO 292
```

```
 262  T(I,J,M)=999
 292  CONTINUE
C
C
      XIDL(1)=0.
      XDL(1)=0.
      XMIS(1)=0.
      XMANT(1)=0.
      DO 293 M=2,MC
      IF(INDE(M).EQ.99)GOTO 294
      XIDL(M)=TIDL(INDE(M))
      XDL(M)=TDL(INDE(M))
      XMIS(M)=TMIS(INDE(M))
      XMANT(M)=TMANT(INDE(M))
      JK=3+M
      JM=INDE(M)+3
      RH(JK)=TRH(JM)
      GOTO 293
 294  XIDL(M)=99
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      XDL(M)=99
      XMIS(M)=99
      XMANT(M)=99
      JK=3+M
      RH(JK)=0
  293 CONTINUE
      DO 317 IC=1,4
 317  RH(IC)=TRH(IC)
       M1=4+MC
       M2=4+MC+NNEW
       RH(M1)=TRH(M2)
      DO 51 I4=1,NICUM
      I5=I4+1
       ELEM(JT,NI,I4)=INDE(I5)
      WRITE(6,832)I4,INDE(I5)
 832  FORMAT(1H1,25X,'MACHINE PLACED IN ',I2,' INCUMBENT MACHINE POSTION
     * IS ',5X,I2)
 51     CONTINUE
      RETURN
      END
C
C
C
C
C     ***************************************************************
C     ***     THIS SUBROUTINE SETS UP THE PARTS ASSIGNMENT PROBLEM    ***
C     ***       BASICALLY, IT DOES THE FOLLOWING:                     ***
C     ***          A. TRANSFORM THE PROBLEM INTO ITS MINIMIZATION     ***
```

```
C    ***             EQUIVALENT                                      ***
C    ***         B. TRANSFORM THE FOUR-VARIABLE ARRAY INTO A         ***
C    ***              ONE-VARIABLE ARRAY. ALL VARIABLES WITH ZERO    ***
C    ***              VALUES ARE TAKEN OUT.                          ***
C    *******************************************************************
C
C
C
C
      SUBROUTINE SETUP(IPA,K,T,DD,X$DL,XDL,X$IDL,XIDL,X$MIS,X$MANT,W,ALP
     *HA,IID,ID,NC1,POB,OBJ,A,NC2,XMIS,XMANT,BH,RH,MC,INFEA)
      DIMENSION K(10),T(10,10,10),DD(10,10),XDL(10),XIDL(10)
      DIMENSION XMIS(10),XMANT(10),IID(10,10,10,10),POB(10)
      DIMENSION A(150,150),OBJ(150),BH(150),RH(20),XMIN(150)
C
C
C     NC1 IS THE TOTAL NUMBER OF BALANCE EQUATIONS
      DO 103 I=1,IPA
      JIN=K(I)
      DO 103 J=1,JIN
      DO 103 M=1,MC
      DO 103 N=1,MC
 103  IID(I,J,M,N)=0
      II=0.
      ID=0.
      NC1=0.
C
```

```
      DO 86 IP=1,IPA
      IKK=K(IP)
      DO 86 IK=1,IKK
       INFEA=0
      DO 60 M=1,MC
      IF(T(IP,IK,M).EQ.999)GO TO 60
      INFEA=INFEA+1
      IF (IK.NE.1)GO TO 65
      NC1=NC1+1.
      ID=ID+1.
      DIS=DD(1,M)
      XYZ=X$DL*XDL(M)+X$IDL*XIDL(M)+X$MIS*XMIS(M)+X$MANT*XMANT(M)
      OBJ(ID)=DIS*W*ALPHA+  T(IP,IK,M)*XYZ/(60.)
      IID(IP,IK,M,1)=ID
      GOTO 60
  65  NC1=NC1+1
      DO 66 IJK=1,MC
      JK=IK-1
      IF(T(IP,JK,IJK).EQ.999)GOTO 66
```

```
      ID=ID+1
      DIS=DD(IJK,M)
      XYZ=X$DL*XDL(M)+X$IDL*XIDL(M)+X$MIS*XMIS(M)+X$MANT*XMANT(M)
      OBJ(ID)=DIS*W*ALPHA+  T(IP,IK,M)*XYZ/(60.)
      IID(IP,IK,M,IJK)=ID
 66   CONTINUE
      IF(IK.NE.IKK)GO TO 60
      ID=ID+1.
      OBJ(ID)=0.
      POB(IP)=ID
      IID(IP,IK,1,1)=ID
 60   CONTINUE
       IF(INFEA.EQ.0)GOTO 940
 86    CONTINUE
C
C
C     THE TOTAL NUMBER OF VARIABLES TO BE SOLVED IS ID
C
C
C     THE A-MATRIX IS NOW CONSTRUCTED
C     THE PART FOR THE BALANCE EQUATIONS IS FIRST CONSTRUCTED
C     THIS PART OF THE A-MATRIX CONSISTS OF SOLELY 1,0,-1.
C
C
C     INITIALIZE
C
C
C
      KNC=NC1+4+MC
      DO 71 I=1,KNC
      DO 71 J=1,ID
 71   A(I,J)=0.
      I=0.
      DO 70 IP=1,IPA
      IKK=K(IP)
      DO 70 IK=1,IKK
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      DO 70 M=1,MC
      IF (T(IP,IK,M).EQ.999)GOTO 70
      IF(IK.NE.1)GOTO 75
      I=I+1
       IJ=IID(IP,1,M,1)
      A(I,IJ)=1.
      JK=IK+1
      DO 76 J=1,MC
      IF(T(IP,JK,J).EQ.999)GOTO 76
      IJ=IID(IP,JK,J,M)
```

```
      A(I,IJ)=-1.
   76 CONTINUE
      GOTO 70
  75  CONTINUE
      I=I+1
      JK=IK-1
      DO 77 J=1,MC
      IF(T(IP,JK,J).EQ.999)GO TO 77
      IJ=IID(IP,IK,M,J)
      A(I,IJ)=1.
  77  CONTINUE
      JK=IK+1
      IF(IK.EQ.IKK)GOTO 74
      DO 78 J=1,MC
      IF(T(IP,JK,J).EQ.999)GOTO 78
      IJ=IID(IP,JK,J,M)
      A(I,IJ)=-1
  78  CONTINUE
      GOTO 70
 74   IJ=IID(IP,IK,1,1)
      A(I,IJ)=-1.
 70   CONTINUE
C
C
C     THE REMAIN OF THE A-MATRIX IS NOW CONTRUCTED
C
C     **THAT IS, COMPLETE THE COEFFICIENTS FOR THE ALLOCATIONS
C       CONTRAINTS**
C
      DO 90 IP=1,IPA
      IKK=K(IP)
      DO 90 IK=1,IKK
      DO 90 M=1,MC
      DO 90 J=1,MC
      IF(IID(IP,IK,M,J).EQ.0)GOTO 90
      IJ=IID(IP,IK,M,J)
      N=NC1+1
      A(N,IJ)=T(IP,IK,M)*XDL(M)
      N=N+1
      A(N,IJ)=T(IP,IK,M)*XIDL(M)
      N=N+1
      A(N,IJ)=T(IP,IK,M)*XMIS(M)
      N=N+1
      A(N,IJ)=T(IP,IK,M)*XMANT(M)
      DO 951 MJ=2,MC
```

```
      IF (MJ.NE.M)GOTO 951
```

```
      NJ=N+MJ-1
      A(NJ,IJ)=T(IP,IK,M)
 951  CONTINUE
      N=N+MC
      A(N,IJ)=DD(J,M)*ALPHA
  90  CONTINUE
      NC2=N
      DO 902 I=1,NC1
 902  BH(I)=0.
      N=NC1+1
      JN=0
      DO 903 I=N,NC2
       JN=JN+1
 903  BH(I)=-1*RH(JN)
      DO 904 I=N,NC2
      DO 904 J=1,ID
 904  A(I,J)=-1*A(I,J)
 940    CONTINUE
      RETURN
      END
C
C******************************************************************
C****     THIS SUBROUTINE DETERMINES THE PRICE-VOLUME          ****
C****      RELATIONSHIP WHICH RESULTS IN THE MAXIMUM           ****
C****       OPERATING PROFIT                                   ****
C******************************************************************
C
C
      SUBROUTINE OPTIMU(A,BH,OBJ,M,N,EPS,OPT,IFLAG,XMIN,XUB,Y,XLL,XUL,P
     *,POB,PB,XOPT,IPA,MC,ID)
      DIMENSION ICOUN(10),ITEMP(10),A(150,150),BH(150),OBJ(150)
      DIMENSION XMIN(150),XUB(150),Y(150),XLL(10,10),XUL(10,10),P(10,5)
      DIMENSION POB(10),PB(10),XOPT(150),TOBJ(150),TDUAL(150),DUAL(150)
      TOPT=0.
      DO 119 I=1,N
  119 XMIN(I)=0.
      IK1=PB(1)
      DO 182 J1=1,IK1
      ICOUN(1)=J1
      IJ=POB(1)
      OBJ(IJ)=(-1)*P(1,J1)
      XMIN(IJ)=XLL(1,J1)
       DO 819 K1=1,IJ
 819  XUB(K1)=XUL(1,J1)
      IF(2.GT.IPA)GOTO 191
      IK2=PB(2)
      DO 183 J2=1,IK2
      MI=POB(1)+1
      IJ=POB(2)
```

```
      ICOUN(2)=J2
      OBJ(IJ)=(-1)*P(2,J2)
      XMIN(IJ)=XLL(2,J2)
       DO 829 K2=MI,IJ
  829 XUB(K2)=XUL(2,J2)
```

```
      IF(3.GT.IPA)GOTO 192
      IK3=PB(3)
      DO 184 J3=1,IK3
      MI=POB(2)+1
      ICOUN(3)=J3
      IJ=POB(3)
      OBJ(IJ)=(-1)*P(3,J3)
      XMIN(IJ)=XLL(3,J3)
      DO 839 K3=MI,IJ
  839 XUB(K3)=XUL(3,J3)
      IF(4.GT.IPA)GOTO 193
      IK4=PB(4)
      DO 185 J4=1,IK4
      MI=POB(3)+1
      ICOUN(4)=J4
      IJ=POB(4)
      OBJ(IJ)=(-1)*P(4,J4)
      XMIN(IJ)=XLL(4,J4)
      DO 849 K4=MI,IJ
  849 XUB(K4)=XUL(4,J4)
      IF(5.GT.IPA)GOTO 194
      IK5=PB(5)
      DO 186 J5=1,IK5
      MI=POB(4)+1
      ICOUN(5)=J5
      IJ=POB(5)
      OBJ(IJ)=(-1)*P(5,J5)
      XMIN(IJ)=XLL(5,J5)
      DO 859 K5=MI,IJ
  859 XUB(K5)=XUL(5,J5)
      CALL LNCAPY(A,BH,OBJ,M,N,EPS,OPT,IFLAG,XMIN,XUB,Y,DUAL)
      IF(OPT.EQ.999)GOTO 185
      OPT=-OPT
       IF(TOPT.GT.OPT)GOTO 186
      TOPT=OPT
      DO 569 II=1,IPA
  569 ITEMP(II)=ICOUN(II)
      DO 567 IM=1,ID
  567 XOPT(IM)=Y(IM)
      DO 1234 IE=1,IPA
 1234  TOBJ(POB(IE))=OBJ(POB(IE))
```

```
       DO 2345 IH=1,M
2345   TDUAL(IH)=DUAL(IH)
 186  CONTINUE
      GOTO 185
 194  CALL LNCAPY(A,BH,OBJ,M,N,EPS,OPT,IFLAG,XMIN,XUB,Y,DUAL)
      IF(OPT.EQ.999)GOTO 184
      OPT=-OPT
      IF(TOPT.GT.OPT)GOTO 185
      TOPT=OPT
       DO 519 II=1,IPA
 519  ITEMP(II)=ICOUN(II)
       DO 517 IM=1,ID
  517 XOPT(IM)=Y(IM)
      DO 1235 IE=1,IPA
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1235   TOBJ(POB(IE))=OBJ(POB(IE))
      DO 2346 IH=1,M
2346   TDUAL(IH)=DUAL(IH)
 185  CONTINUE
      GOTO 184
 193  CALL LNCAPY(A,BH,OBJ,M,N,EPS,OPT,IFLAG,XMIN,XUB,Y,DUAL)
      IF(OPT.EQ.999)GOTO 183
      OPT=-OPT
      IF(TOPT.GT.OPT)GOTO 184
      TOPT=OPT
      DO 529 II=1,IPA
 529  ITEMP(II)=ICOUN(II)
      DO 527 IM=1,ID
  527   XOPT(IM)=Y(IM)
      DO 1236 IE=1,IPA
1236   TOBJ(POB(IE))=OBJ(POB(IE))
      DO 2347 IH=1,M
2347  TDUAL(IH)=DUAL(IH)
 184  CONTINUE
      GO TO 183
 192  CALL LNCAPY(A,BH,OBJ,M,N,EPS,OPT,IFLAG,XMIN,XUB,Y,DUAL)
      IF(OPT.EQ.999)GOTO 182
      OPT=-OPT
      IF(TOPT.GT.OPT)GOTO 183
      TOPT=OPT
      DO 539 II=1,IPA
  539 ITEMP(II)=ICOUN(II)
      DO 537 IM=1,ID
 537  XOPT(IM)=Y(IM)
       DO 1237 IE=1,IPA
1237   TOBJ(POB(IE))=OBJ(POB(IE))
       DO 2348 IH=1,M
2348   TDUAL(IH)=DUAL(IH)
```

```
 183  CONTINUE
      GOTO 182
 191  CALL LNCAPY(A,BH,OBJ,M,N,EPS,OPT,IFLAG,XMIN,XUB,Y,DUAL)
      IF(OPT.EQ.999)GOTO 989
      OPT=-OPT
      IF(TOPT.GT.OPT)GO TO 182
      TOPT=OPT
      DO 549 II=1,IPA
 549  ITEMP(II)=ICOUN(II)
      DO 547 IM=1,ID
 547  XOPT(IM)=Y(IM)
      DO 1238 IE=1,IPA
1238   TOBJ(POB(IE))=OBJ(POB(IE))
       DO 2337 IH=1,M
2337    TDUAL(IH)=DUAL(IH)
  182  CONTINUE
 989  OPT=TOPT
      DO 1239 IE=1,IPA
1239   OBJ(POB(IE))=TOBJ(POB(IE))
C       NCJ=M-9
C     WRITE(6,5646)
C     DO 2212 IL=1,M
```

```
C       IW=NCJ+IL
C5646  FORMAT(25X,'THE DUALS FOR THE ALLOCATION CONSTRAINTS ARE : ')
C     WRITE(6,*)IL,TDUAL(IL)
C
 2212 CONTINUE
      RETURN
      END
C
```

APPENDIX IV

```
*******************************************************************
C**   THE FOLLOWING LINEAR PROGRAM WAS DEVELOPED BY WARREN ADAMS   **
C**   , PH.D. STUDENT VPI.SU., FOR HIS GRADUATE RESEARCH WORK.     **
C**   THIS AUTHOR WOULD LIKE TO THANK HIM FOR MAKING THIS ROUTINE **
C**   ACCESSIBLE. THIS IS A MINIMIZATION ROUTINE WITH GREATER THAN**
C**   AND EQUAL TO INEQUALIES .                                    **
C******************************************************************
      SUBROUTINE LNCAPY(A,BH,OBJ,M,N,EPS,OPT,IFLAG,XMIN,XUB,Y,DUAL)
C
C     THIS SUBROUTINE SOLVES A LINEAR PROGRAMMING PROBLEM WITH UPPER
C     BOUNDING ON THE VARIABLES.  THE REVISED SIMPLEX METHOD IS USED,
C
C
      COMMON/WAR/NBASIC(150),RHS(150),NUPPER(150),SURROG(150),AVALU
      DIMENSION A(150,150),BINV(150,150),B(150),OBJ(150),TEMP(150)
      DIMENSION NFLAG(300),DUAL(150),XMIN(150),XUB(150),XMAX(150),BH(150
     *),Y(150)
C
C     IFLAG=0 IMPLIES NO STRONGEST SURROGATE CONSTRAINT IS CALCULATED.
C     ADJUST UPPER BOUNDS AND RIGHT HAND SIDES
      DO 500 I=1,N
  500 XMAX(I)=XUB(I)-XMIN(I)
      DO 501 I=1,M
      SUM=0.0
      DO 502 J=1,N
 502  SUM=SUM+A(I,J)*XMIN(J)
 501  B(I)=BH(I)-SUM
C     WRITE(6,288)
C288  FORMAT(10X,'THE RIGHT HAND SIDE OF THE MATRIX IS AS FOLLOWS :',2X,
C    *'(ALL COEFF CONVERTED TO MINIMIZATION EQUIVALENT)',///)
C     WRITE(6,*)(B(I),I=1,M)
      ICOUNT=1
      AMAX=B(1)
      DO 1 I=2,M
      IF(B(I).LE.AMAX) GO TO 1
      ICOUNT=I
      AMAX=B(I)
    1 CONTINUE
C     INITIALIZE B INVERSE AND UPDATE THE RIGHT HAND SIDE.
      DO 2 J=1,M
      DO 2 I=1,M
      BINV(I,J)=0.
    2 IF(I.EQ.J) BINV(I,J)=-1.
      DO 3 I=1,M
      BINV(I,ICOUNT)=1.
    3 RHS(I)=AMAX-B(I)
      RHS(ICOUNT)=AMAX
C     INITIALIZE NO VARIABLES AT UPPER BOUND.
      DO 4 I=1,N
```

```
    4 NUPPER(I)=0
```

```
C     INITIALIZE BASIC VARIABLES.  (N+M+1) SIGNIFIES ARTIFICIAL.
      DO 5 I=1,M
    5 NBASIC(I)=N+I
      NBASIC(ICOUNT)=N+M+1
C     INITIALIZE DUAL VARIABLES AND OBJECTIVE FUNCTION VALUE.
      DO 6 I=1,M
    6 DUAL(I)=0.
      DUAL(ICOUNT)=1.
      OBJECT=-AMAX
      NPLUSM=N+M
C     SET FLAG FOR BASIC VARIABLES.  (1 = BASIC,  0 = NONBASIC).
      DO 7 I=1,N
    7 NFLAG(I)=0
      NPLUS1=N+1
      NPLUS=N+M+1
      DO 8 I=NPLUS1,NPLUS
    8 NFLAG(I)=1
      NFLAG(N+ICOUNT)=0
      IPHASE=1
C     BEGIN PHASE 1.
C   9 IF(OBJECT.LE.-EPS) GO TO 14
    9 IF(NBASIC(ICOUNT).EQ.NPLUS.AND.RHS(ICOUNT).GT..04)GO TO 14
      IPHASE=2
C     REDEFINE DUAL VARIABLES AND OBJECTIVE FUNCTION VALUE AT BEGINNING
C     OF PHASE 2.
      OBJECT=0.
      DO 12 I=1,M
      DUAL(I)=0.
      IP=I+N
      IF(NFLAG(IP).EQ.1) GO TO 11
      DO 10 J=1,M
      NU=NBASIC(J)
      IF(NU.GT.N) GO TO 10
      DUAL(I)=DUAL(I)+OBJ(NU)*BINV(J,I)
   10 CONTINUE
   11 NB=NBASIC(I)
      IF(NB.LE.N)OBJECT=OBJECT-OBJ(NB)*RHS(I)
   12 CONTINUE
      DO 13 I=1,N
   13 IF(NUPPER(I).EQ.1)OBJECT=OBJECT-OBJ(I)*XMAX(I)
C     FIND COLUMN TO SERVE AS PIVOT COLUMN.
C     SET IMARK EQUAL TO 1 (0) IF VARIABLE IS (NOT) AT UPPER BOUND.
   14 ISTART=0
      DO 21 I=1,N
      IF(NFLAG(I).EQ.1) GO TO 21
```

```
      IF(IPHASE.EQ.1)RC=0.
      IF(IPHASE.EQ.2)RC=OBJ(I)
      DO 15 J=1,M
   15 RC=RC-DUAL(J)*A(J,I)
C     CHECK IF VARIABLE IS AT UPPER BOUND.
      IF(NUPPER(I).EQ.1) GO TO 18
      IF(ISTART.NE.0) GO TO 16
      ISTART=1
      GO TO 17
   16 IF(RC.GE.AMIN) GO TO 21
```

```
   17 AMIN=RC
      ICOL=I
      IMARK=0
      GO TO 21
   18 IF(ISTART.NE.0) GO TO 19
      ISTART=1
      GO TO 20
   19 IF(-RC.GE.AMIN) GO TO 21
   20 AMIN=-RC
      ICOL=I
      IMARK=1
   21 CONTINUE
      IF(ISTART.EQ.0) AMIN=0.
      IST=0
      DO 22 I=NPLUS1,NPLUSM
      IST=IST+1
      IF(NFLAG(I).EQ.1.OR.DUAL(IST).GE.AMIN-EPS) GO TO 22
      AMIN=DUAL(IST)
      ICOL=I
      IMARK=0
   22 CONTINUE
      IF(AMIN.GE.-.04) GO TO 29
C     CALCULATE PIVOT COLUMN.
      IF(ICOL.GT.N) GO TO 25
      DO 23 I=1,M
   23 TEMP(I)=0.
      DO 24 I=1,M
      DO 24 J=1,M
   24 TEMP(I)=TEMP(I)+BINV(I,J)*A(J,ICOL)
      GO TO 27
   25 IST=ICOL-N
      DO 26 I=1,M
   26 TEMP(I)=-BINV(I,IST)
   27 IF(IMARK.EQ.1) GO TO 28
C     ENTERING VARIABLE IS NONBASIC AT VALUE 0.  UPDATE CURRENT TABLEAU.
      CALL UPDAT1(TEMP,RHS,NBASIC,NFLAG,DUAL,BINV,NUPPER,ICOL,AMIN,
```

```
     *M,N,EPS,OBJECT,IPHASE,NPLUS,XMAX)
      IF(IPHASE.EQ.1) GO TO 9
      GO TO 14
C
C     ENTERING VARIABLE IS NONBASIC AT UPPER BOUND 1.  UPDATE CURRENT
C     TABLEAU.
C
   28 CALL UPDAT2(TEMP,RHS,NBASIC,NFLAG,DUAL,BINV,NUPPER,ICOL,AMIN,
     *M,N,EPS,OBJECT,IPHASE,NPLUS,XMAX)
      IF(IPHASE.EQ.1) GO TO 9
      GO TO 14
   29 IF(IPHASE.EQ.1) GO TO 33
C     LINEAR PROGRAM TERMINATED.
      OPT=-OBJECT
      IF(IFLAG.EQ.0)GO TO 35
C     CALCULATE THE STRONGEST SURROGATE CONSTRAINT.
      DO 32 I=1,N
      IF(NFLAG(I).EQ.0)GO TO 30
      SURROG(I)=OBJ(I)
```

```
      GO TO 32
   30 SURROG(I)=0.
      DO 31 J=1,M
   31 SURROG(I)=SURROG(I)+DUAL(J)*A(J,I)
   32 CONTINUE
      AVALU=0.
      DO 36 J=1,M
   36 AVALU=AVALU+DUAL(J)*B(J)
      GO TO 35
  33  OPT=999
      GO TO 91
   35 CONTINUE
C     WRITE(6,800)
C 800 FORMAT(1H1,25X,'THE SHADOW PRICES AT OPTIMALITY ARE AS FOLLOWS',//
C    *)
C     DO 333 I=1,M
C 333 WRITE(6,273)I,DUAL(I)
C273  FORMAT(25X,I2,10X,F8.2)
C     REMOVES OPTIMAL VARIABLES
      DO 600 I=1,N
      Y(I)=XMIN(I)
      IF(NUPPER(I).EQ.1)Y(I)=XUB(I)
 600  CONTINUE
      DO 601 I=1,M
      IF(NBASIC(I).LE.N)Y(NBASIC(I))=RHS(I)+XMIN(NBASIC(I))
 601  CONTINUE
      DO 90 J=1,N
```

```
   90 OPT=OPT+OBJ(J)*XMIN(J)
C     WRITE(6,*)OPT
C     WRITE(6,*)NFLAG(NPLUS),NBASIC(ICOUNT),RHS(ICOUNT)
 91   RETURN
      END
      SUBROUTINE UPDAT1(TEMP,RHS,NBASIC,NFLAG,DUAL,BINV,NUPPER,ICOL,
     *AMIN,M,N,EPS,OBJECT,IPHASE,NPLUS,XMAX)
C     THIS SUBROUTINE UPDATES THE CURRENT TABLEAU GIVEN THAT THE
C     ENTERING VARIABLE IS NONBASIC AT VALUE 0.
C
      DIMENSION TEMP(150),RHS(150),NBASIC(150),NFLAG(300),DUAL(150),
     *BINV(150,150),NUPPER(150),XMAX(150)
      IMARKE=0
      ISTART=0
      DO 7 I=1,M
      RT=RHS(I)
      SPOT=TEMP(I)
      IF(SPOT.LE.EPS) GO TO 3
      RATIO=RT/SPOT
      IF(ISTART.NE.0) GO TO 1
      ISTART=1
      GO TO 2
    1 IF(RATIO.GE.THETA) GO TO 7
    2 THETA=RATIO
      IROW=I
      IMARKE=0
      GO TO 7
    3 IF(SPOT.GE.-EPS)GO TO 7
```

```
      IF (NBASIC(I).NE.NPLUS.OR.IPHASE.EQ.1)GO TO 4
      THETA=0.
      IROW=I
      IMARKE=0
      GO TO 9
    4 IF(NBASIC(I).GT.N)GO TO 7
      RATIO=(RT-XMAX(NBASIC(I)))/SPOT
      IF(ISTART.NE.0) GO TO 5
      ISTART=1
      GO TO 6
    5 IF(RATIO.GE.THETA) GO TO 7
    6 THETA=RATIO
      IROW=I
      IMARKE=1
    7 CONTINUE
      IF(ISTART.EQ.0.AND.ICOL.GT.N)GO TO 14
      IF(ISTART.EQ.0)THETA=XMAX(ICOL)
      IF(ICOL.GT.N)GO TO 9
```

```
      IF(THETA.LT.XMAX(ICOL)-EPS)GO TO 9
C     ENTERING VARIABLE CHANGES FROM NONBASIC WITH VALUE 0 TO NONBASIC
C     WITH VALUE 1.  UPDATE NUPPER, RHS, AND OBJECT.
      NUPPER(ICOL)=1
      DO 8 I=1,M
    8 RHS(I)=RHS(I)-TEMP(I)*XMAX(ICOL)
      OBJECT=OBJECT-AMIN*XMAX(ICOL)
      GO TO 16
C     ENTERING VARIABLE CHANGES FROM NONBASIC WITH VALUE 0 TO BASIC.
    9 IF(IMARKE.EQ.1) NUPPER(NBASIC(IROW))=1
      NFLAG(NBASIC(IROW))=0
      NBASIC(IROW)=ICOL
      NFLAG(ICOL)=1
      SPOT=TEMP(IROW)
      DO 10 J=1,M
   10 BINV(IROW,J)=BINV(IROW,J)/SPOT
      RHS(IROW)=THETA
      DO 12 I=1,M
      IF(I.EQ.IROW) GO TO 12
      SPOT=TEMP(I)
      IF(SPOT.GE.-EPS.AND.SPOT.LE.EPS) GO TO 12
      RHS(I)=RHS(I)-SPOT*THETA
      DO 11 J=1,M
   11 BINV(I,J)=BINV(I,J)-SPOT*BINV(IROW,J)
   12 CONTINUE
      DO 13 J=1,M
   13 DUAL(J)=DUAL(J)+AMIN*BINV(IROW,J)
      OBJECT=OBJECT-AMIN*THETA
      DO 80 I=1,M
      IPT=I+N
      IF(NFLAG(IPT).EQ.1)DUAL(I)=0.
   80 CONTINUE
      GO TO 16
   14 WRITE(6,15)
   15 FORMAT(1X,'ERROR.  CAPY APPEARS UNBOUNDED')
      WRITE(6,*)(TEMP(I),I=1,M)
      WRITE(6,*)IPHASE,AMIN
```

```
      STOP
   16 CONTINUE
      RETURN
      END
      SUBROUTINE UPDAT2(TEMP,RHS,NBASIC,NFLAG,DUAL,BINV,NUPPER,ICOL,
     *AMIN,M,N,EPS,OBJECT,IPHASE,NPLUS,XMAX)
C
C     THIS SUBROUTINE UPDATES THE CURRENT TABLEAU GIVEN THAT THE
C     ENTERING VARIABLE IS NONBASIC AT VALUE 1. (UPPER LIMIT).
```

```
      DIMENSION TEMP(150),RHS(150),NBASIC(150),NFLAG(300),DUAL(150),
     *BINV(150,150),NUPPER(150),XMAX(150)
      IMARKE=0
      ISTART=0
      DO 7 I=1,M
      RT=RHS(I)
      SPOT=TEMP(I)
      IF(SPOT.GE.-EPS) GO TO 3
      RATIO=(RT+SPOT*XMAX(ICOL))/SPOT
      IF(ISTART.NE.0) GO TO 1
      ISTART=1
      GO TO 2
    1 IF(RATIO.LE.THETA) GO TO 7
    2 THETA=RATIO
      IROW=I
      IMARKE=0
      GO TO 7
    3 IF(SPOT.LE.EPS) GO TO 7
      IF(NBASIC(I).NE.NPLUS.OR.IPHASE.EQ.1)GO TO 4
      THETA=XMAX(ICOL)
      IROW=I
      IMARKE=0
      GO TO 9
    4 IF(NBASIC(I).GT.N)GO TO 7
      RATIO=(RT+SPOT*XMAX(ICOL)-XMAX(NBASIC(I)))/SPOT
      IF(ISTART.NE.0) GO TO 5
      ISTART=1
      GO TO 6
    5 IF(RATIO.LE.THETA) GO TO 7
    6 THETA=RATIO
      IROW=I
      IMARKE=1
    7 CONTINUE
      IF(ISTART.EQ.0)THETA=0.
      IF(ICOL.GT.N.OR.THETA.GT.EPS) GO TO 9
C     ENTERING VARIABLE CHANGES FROM NONBASIC WITH VALUE 1 TO NONBASIC
C     WITH VALUE 0.  UPDATE NUPPER, RHS, AND OBJECT.
      NUPPER(ICOL)=0
      DO 8 I=1,M
    8 RHS(I)=RHS(I)+TEMP(I)*XMAX(ICOL)
      OBJECT=OBJECT-AMIN*XMAX(ICOL)
      GO TO 14
C     ENTERING VARIABLE CHANGES FROM NONBASIC WITH VALUE 1 TO BASIC.
    9 NUPPER(ICOL)=0
      IF(IMARKE.EQ.1) NUPPER(NBASIC(IROW))=1
      NFLAG(NBASIC(IROW))=0
```

```
      NBASIC(IROW)=ICOL
      NFLAG(ICOL)=1
      SPOT=TEMP(IROW)
      DO 10 J=1,M
   10 BINV(IROW,J)=BINV(IROW,J)/SPOT
      RHS(IROW)=THETA
      DO 12 I=1,M
      IF(I.EQ.IROW) GO TO 12
      SPOT=TEMP(I)
      IF(SPOT.GE.-EPS.AND.SPOT.LE.EPS) GO TO 12
      RHS(I)=RHS(I)+SPOT*XMAX(ICOL)-SPOT*THETA
      DO 11 J=1,M
   11 BINV(I,J)=BINV(I,J)-SPOT*BINV(IROW,J)
   12 CONTINUE
      DO 13 J=1,M
   13 DUAL(J)=DUAL(J)-AMIN*BINV(IROW,J)
      OBJECT=OBJECT-AMIN*(XMAX(ICOL)-THETA)
   14 CONTINUE
      DO 80 I=1,M
      IPT=I+N
      IF(NFLAG(IPT).EQ.1)DUAL(I)=0.
   80 CONTINUE
      RETURN
      END
```

APPENDIX V.

COMPUTATIONAL ASPECTS

This problem was run on an IBM 3081 series D24 computer. In the beginning, several test problems were solved using the Fortran G compiler. For this compiler, the compilation time was roughly 6 sec; the execution time was around 59 minutes. Upon examining the results, in order to obtain the final optimal replacement sequence, as many as 2000 linear programming each of about 100 variables and 60 constraints were solved.

Then, the same test problems were run using the "Fortran H extended compiler. Fortran H provides more accuracy as well as optimization of compiling. According to the User's Guide FT04, published by the Virginia Tech Computer Center, there are three options: "... OPT = 0 means the compiler does no optimization. OPT = 1 implies that the compiler is to treat each source program as a single program loop and is to optimize the loop according to allocation and branching. OPT = 2 implies that the compiler is to treat each source program as a collection of loops and is to optimize each loop with regard to register allocation, branching, common expression elimination, and replacement of redundant computations." Option one was first applied. The results were virtually identical except that the compilation took 11 sec and the execution took 1 hour 12 minutes. Option two was then applied. The compilation again took 11 seconds but the execution time was significantly lessened --it took merely 26 minutes approximately. In other words, for the solution procedure (the FORTRAN program) used for this research, the FORTRAN H compiler with option 2 took only 45% CPU time of that of FORTRAN G compiler and 36% of that of FORTRAN H option one.

Another computational element concerns the use of tolerance parameters in the linear program subroutine (LNCAPY). According to Warren P. Adams who developed the subroutine, the following are the parameter specifications and their implications:"

EPS: At the value of .000001. When pivoting in the linear program procedure, an element in the A-matrix with value in the interval [-.000001, .000001] is assumed to have a value of zero.

EPS2: At the value of .04. This tolerance parameter is used to determine whether a variable is a candidate to become basic. The stopping criteria is when all reduced costs are greater than or equal to EPS2.

In a typical minimization linear programming, the stopping criteria is based on all reduced costs being negative; her, it stops when all reduced costs are greater than or equal to some predetermined tolerance (EPS2). One must judiciously choose this EPS2 so that tradeoff between accuracy and CPU time is desirable. In the case where EPS2 is set too large, optimality may not be achieved while in the case where EPS2 is set too small, CPU time increases. Based upon experimental testing, EPS2 tends to perform well in the range (.04, .07). A note of caution here is not to set EPS2 close to zero. The LNCAPY subroutine may either declare the linear program infeasible (which is in fact feasible) or pivot indefinitely."