AN EVALUATION PROCESS FOR MATERIAL HANDLING SYSTEMS WITHIN FMS

BY

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(ABSTRACT)

The problem of evaluating new manufacturing technologies, in particular, flexible manufacturing systems (FMS) is a complex one, as its interdisciplinary nature involves multiple variables. These variables are qualitative as well as quantitative, strategic, as well as technological, intangible as well as tangible. This dissertation deals with the problem of the overall evaluation process, in particular, the evaluation of material handling systems within FMS. In particular, automated guided vehicle systems (AGVS) are studied from a technical viewpoint, as they are related to strategic and economic considerations.

Two main evaluation frameworks are developed. One integrates multiattribute decision models, namely, the analytic hierarchy process or AHP and the displaced ideal model (DIM), and the other integrates analytical techniques with simulation modeling. As a by product, flexibility indices are also developed for AGVS and linked to the fundamental aspects of the evaluation of new technologies. This research also shows how analytical techniques can be combined with simulation modeling to form a more extensive evaluation process that includes opportunity costs as well as the usual tangible costs. Finally, a technical analysis of FMS/AGVS is done on some typical cell configurations using the flexibility indices developed in this research.

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I-INTRODUCTION

1.1 THE PROBLEM

This dissertation is concerned with the problem of evaluating materials handling systems (MHS), in particular, with respect to their flexibilities within flexible manufacturing systems (FMS). Material handling systems such as conveyors and automated guided vehicles (AGVS) do contribute in routing, volume and expansion flexibilities, which are essential for the overall flexibility of a production system. Routing flexibility measures the ability to handle breakdowns while continuing to produce the desired set of part types. Volume flexibility measures the ability to operate an FMS profitably at different production volumes. Expansion flexibility represents the capability of expanding an FMS as needed, easily and modularly (Stecke and Browne, 1985). These flexibilities are thought of as being closely related to material handling systems, as they attempt to measure flow and layout characteristics.Other types of flexibility can also be defined for machines and cells. However, this research concentrated on measures especially devised for materials handling systems. In particular, questions of interest were first of all how much of these flexibilities are necessary for a given firm, and which MHS provides the best mix of these capabilities ? What are opportunity costs associated with a certain level of flexibility emerging from a particular MHS ?

Flexibility is not a new concept in manufacturing. However, this aspect of production technology is now a strategic issue in the face of an economic environment that has become more *turbulent* (that is more complex and unpredictable), and as it is related to capital intensive investments which have themselves strategic implications. Dealing successfully with turbulent environments requires quick response to market change, shorter lead time and product differentiation, in other words, characteristics closely related to flexibility. Flexible manufacturing systems are aimed at responding to such environments by producing low volume goods efficiently.

According to Eversheim and Hermann (1982), trends in manufacturing automation are the following:

- The increase of flexibility of manufacturing systems in order to improve response to market changing conditions,

- the use of automated handling equipment working 24 hours a day unattended, and

- handling equipment that is more adaptable to special handling needs.

Firms therefore need to be flexible to changes in product demand level and product variety. Requirements necessary to counteract these market disturbances are: 1. the ability to modify the product quickly, 2. the ability to change production levels efficiently, and 3. the ability to expand the manufacturing system.

Material handling systems provide time and space utility (Tompkins and White, 1984). Not only do they support manufacturing capabilities, but they are an integral part of what makes a system flexible, since they are responsible for the overall flow of materials. A *flexible* material handling system will be able to fully exploit the capabilities of manufacturing cells that have short set up times, alternative ways of producing a given part , and the possibility of interchanging operations for a given part type. Thus, the overall production flexibility of a manufacturing system depends on the flexibility of its material handling system, as well as its machine tools (Stecke and Browne, 1985).

Yet, the current evaluation of materials handling systems is based only on traditional accounting and engineering economy techniques in a single criterion decision making fashion. According to Frazelle (1985), MHS are still being largely assessed on their resulting return on investment (ROI). Muther and Haganäs (1969), in their systematic handling analysis, take into account versatility and adaptability of the handling methods to daily fluctuations in products and flexibility in terms of the ease of changing or rearranging the installed methods. However, their economic analysis includes traditional costs only. Groover (1987) refers to an efficiency measure of performance including the proportion of empty traveling time and a traffic congestion factor. Kulwiek (1986) mentions intangible factors including flexibility but refers nonetheless to payback and gross rate of return when evaluating MHS. No explicit measures of flexibility are given that could be integrated (in a multiattribute fashion) with other traditional costs such as first and operating costs.

According to Sullivan (1986), "...traditional measures of project worth such as return on investment (ROI), payback, and net present worth, are conceptually inadequate for judging the strategic merits of computer integrating manufacturing (CIM) technologies. However, these measures continue to be used for lack of a more acceptable approach."

An evaluation based only on the usual costs concepts does not recognize the strategic implications of flexibility in terms of opportunity costs of not having the right amount of responsiveness, reliability, etc. " A failure to quantify [flexibility] leads us down the path toward expensive ultimate capability in those areas" (Apple and McGinnis, 1987). Likewise it can lead to a choice of system that provides inadequate flexibility and that might need to be upgraded in the future (Jones, 1987). Furthermore, no techniques are available that would describe trade-offs between conventional costs and the opportunity costs associated with the flexibility of alternative material handling systems.

The problem is therefore to quantify the value of flexibility, so that opportunity costs may be assessed. This leads to developing an overall measure of flexibility which, in turn, leads to analyzing it in terms of its components. Indices of flexibility should then be developed for each of these components (namely, routing, volume and expansion flexibilities) in order to assess alternative MHS from a operational standpoint. Each of these flexibility indices should be weighted according to their strategic implications for the firm (what type of flexibility is more important than the others with respect to the firm's previously stated super ordinate goals). Finally, the overall flexibility of these MHS has to be integrated with costs to get a final measure of worth or value.

1.2 BENEFITS FOR INDUSTRY

The benefits for industry likely to follow from this research are :

1. An increased understanding of the effects of materials handling system on a production system.

2. An improved assessment of the several flexibilities emerging from these handling systems as they are integrated with manufacturing cells.

3. A better estimate of the value of flexibility.

4. The possibility for implementing a decision support system (DSS) specifically designed for material handling systems in order to justify and select a materials handling system (or a combination of MHS) , where opportunity costs are included as well as first and operations costs.

1.3 OBJECTIVES AND SIGNIFICANCE

The objectives of this research were to first of all develop two evaluation processes for material handling systems within FMS (especially AGVS) and flexibility indices for these systems. These indices were then integrated (with other data) in a multiattribute fashion using available techniques from the multiple criteria decision making field on the one hand and within an iterative process on the other hand.

At least two types of material handling systems are found within FMS: conveyors and automated guided vehicle system. Robots are also used but as a secondary MHS, linking the primary MHS to machines or cells. Though in certain cases conveyors can be used instead of AGVS within FMS , this dissertation concentrated on the latter. This was because AGVS are used more and more in manufacturing and assembly systems, receiving/shipping, warehousing, production transportation and other areas. Overall demand for these AGVS is growing steadily (Hammond, 1987). Several advantages are offered by AGVS. Among them are (McEllin, 1987):

"• Capability of full computer control and also the ability to integrate the system in an overall production unit host management computer.

• Ability to cope with complex or random workpiece or product routing, including varying production rate.

• The flexibility to adapt to changes in product design and factory machine layouts without further major capital expenditure.

• The ability to extend the machine layout, number of operating stations, etc, at low cost.

• Ability to have a variety of vehicles performing different functions while operating on the same circuit.

• Freedom to plan factory layouts, without the restrictions normally imposed on conveying systems.

• Individual breakdown or interruptions in either the process or handling system do not disturb the whole system.

• The AGV control system will allow fully automated, semi-automatic or direct manual control. This is particularly important in the event of failure of some element of the production system, in order to ensure the continued availability of the handling system. "

Another reason for concentrating on these particular systems is their complexity which necessitates a thorough study both at the system design and economic evaluation stages. More specifically, the system analysis done in Chapter V concerns AGVS. The flexibility indices were developed with AGVS in mind; however, some of these measures could either be used or adapted to conveyor systems. Thus, most of this research concerns AGVS within FMS; however, some parts of this dissertation discuss conveyors, since these conventional MHS can also be used in FMS.

The results of this research should be significant for organizations that already have *unlinked* manufacturing cells (or islands of automation) and are ready to integrate their production process via a materials handling system whose flexibility is compatible with the existing capability of these cells. Designers of these cells and of materials handling systems destined for FMS may also benefit from this research as the developed flexibility indices will provide additional design criteria up front, in the early stages of the development of these systems. Such information should improve the understanding and prediction of the behavior of flexible manufacturing systems before they are implemented. This research should also benefit strategic planners who attempt to *merge strategy with operations*. The capability of a firm to provide differentiated products in a timely manner is likely to be related to the flexibility (-ies) of its production system. Flexibility indices are likely to link strategic issues with the technological means necessary to reach overall business goals. Finally, this research project presents an evaluation process that could lead to the evaluation of manufacturing technologies other than material handling systems. More specifically, it offers the following improvements over previous evaluation procedures of manufacturing systems:

- A justification procedure more extensive than classical ROI and other financial measures of performance (integrating technical, economic, tangible and intangible aspects of MHS).

• All "costs" are assessed instead of first and operating costs.

• Operational characteristics of material handling systems are linked with superordinate goals of the firm, so that the selected alternative is more in line with the strategic aspects of these goals.

• A selection procedure that takes into account conflicting objectives to be used instead of conventional engineering economy techniques which optimize only one measure of merit, thus missing trade-offs between variables of differing types. Such conflicts may arise when maximizing all flexibility types while minimizing first costs and opportunity costs. Conflicts may also arise between flexibility types. For example, volume flexibility may hinder routing flexibility as increasing traffic or flow within the system (by adding AGVS for example) makes re-routing more difficult. Expansion flexibility may also have a negative impact on routing flexibility, since the addition of cells increase the complexity of the system, thereby decreasing its overall reliability.

• A multiattribute analysis that integrates functional and structural dependencies among variables that affect a system.

Finally, as it was previously noted, a selection procedure that integrates several conflicting variables may have an impact on the design process. It may indicate, for instance, the direction of search for new alternatives that *reduce* the conflict, in the sense that they get closer to an *ideal* alternative. (These concepts of conflict reduction and ideal alternative will be made more explicit in the second chapter where multiple criteria decision models are described).

1.4 OVERVIEW OF RESEARCH

The next chapter presents a review of the literature where the following topics are discussed: the problem of evaluating new manufacturing technologies, flexible manufacturing systems, concepts and measures of flexibility (-ies), multiple decision making techniques, and analysis techniques for FMS.

Chapter III describes the research approach; in particular, the development of the evaluation frameworks and the flexibility indices. The next chapter then analyzes flexibility from different perspectives. In particular, strategic, economic, and technical considerations are explored.

Chapter V describes the design problems associated with AGVS within FMS; in particular, this part attempts to understand the interdependencies between these variables from an operational or system viewpoint. The second part of this chapter develops flexibility indices for AGVS. In one framework, these indices are integrated in a multiple criteria approach such as the analytic hierarchy process and the displaced ideal model. In another framework, analytical models are combined with simulation modeling.

The next chapter examines two important aspects which are theoretical underpinnings of the problem of evaluating new manufacturing technologies: the concepts of opportunity costs and economies of scope. This part of the research suggests how the indices are to be integrated with these aspects, especially opportunity costs.

Chapter VII describes frameworks for evaluating new manufacturing technologies (in particular, MHS within FMS) are developed. They include systematic procedures that attempt to take into account the multiple aspects of these technologies. In this part, it is shown how existing analytical techniques can be combined with simulation modeling.

Finally, Chapter IX analyzes, from a technical standpoint, typical FMS/AGVS using *combined* simulation. The simulation software package used there combines both discrete events and continuous variables. The discrete part models the flow of loads within the FMS while the continuous part tracks vehicle movements. Some of the flexibility indices are used in the analysis, and the difficulties of applying the indices to real cases are pointed out.

The last Chapter concludes this research. Extensions are proposed that would improve the evaluation process and the use of the indices.

II-REVIEW OF LITERATURE

In this section, several topics are covered. This is due to the complexity of the evaluation problem as it has ramifications into the technical, economic and managerial fields. Among other things, this multi-dimensional aspect indicates that multi-criteria tools should be used and integrated in the evaluation process. This is why, among other things, two particular methods or techniques that seem well suited to the reality of decision making are described. But, before this is done, other subjects equally important for this research are reviewed. First, the problem of evaluation of new manufacturing technology is explained in terms of strategic issues and basically justifies the need for integration from that standpoint. Then, types of materials handling systems that are typically found within FMS are described as well as their particular role in these systems, both with respect to opportunity costs and economies of scope. The next subsection will review flexibility measures devised for production systems in general and FMS in particular. Two multi criteria approaches, the analytic hierarchy process (AHP) and the displaced ideal model (DIM), are then described. Decision support systems (DSS) that have been designed for material handling systems are mentioned. Finally, the analysis of FMS is briefly described.

II-1.THE EVALUATION PROBLEM

New manufacturing technologies, in particular flexible manufacturing systems (FMS), are known to present difficulties in their technical and economic evaluation. These problems come from the following factors: lack of information, intangibles (response time, minimum inventory, improved manufacturing control, etc.), flexibility concepts, inadequate accounting procedures, and overall effects of FMS on the organizations (Primrose and Leonard, 1986). From a managerial aspect, there is no comprehensive justification methodology that considers long-term competitive advantages of the firm, that is, there is a misfit between tactical/strategic decision patterns and organization structure. Moreover, the strategic benefits of investments such as FMS are not well linked with their operational characteristics (Choobineh, 1986; Skinner, 1986; Meredith and Nallan, 1986). According to Romano (1985), "...CIM [computer integrated manufacturing] is most effective when used to achieve specific operational goals that have been defined as a part of a broader business strategy". This work addresses that particular problem in part by using the analytic hierarchy process (AHP) for which applications in strategic planning have been developed (Saaty and Kearns, 1985).

Some models have been developed for MHS evaluation. One study (Shelton and Jones,1987) uses a multiattribute approach with a comprehensive list of technical parameters for AGVS. Another one is a knowledge based design aid that combines methodologies from expert systems and decision sciences (Gabbert and Brown, 1987). Finally, an expert system has been developed for an extensive range of material handling systems with true expertise was being used in building the model (Fisher, et al, 1987).

II-2. FLEXIBLE MANUFACTURING SYSTEMS

Theoretically, a flexible manufacturing system is an attempt to combine the efficiency and productivity of a production line with the flexibility of a job shop, by generating economies of scope

(Jelinek and Goldhar, 1985; Kusiak, 1985). According to Ránky, (1986), the FMS system architecture is comprised of the following elements:

1. Highly automated and programmable cells.

2. Linking system that integrates these cells .

3. Part, tool, and pallet storage facility (AS/RS).

4. High level computer control (distributed processing system).

5. Dynamic control system (dynamic scheduling).

Materials handling systems typically encountered when designing an FMS are : automated guided vehicles (AGVS), conveyors, industrial robots, special purpose pallet changing and pallet transportation systems, and forklift trucks (Groover, 1987; Ránky, 1986). The basic role of MHS within FMS is one of integration (Bullinger, et al, 1986; Kusiak, 1985; Chakravarty,1987; Modern Material Handling, 1987; Apple and McGinnis, 1987; Zisk, 1983), as they affect raw materials, inspection of raw materials, part manufacturing, test and inspection, assembly, packaging, shipping, and as they link different FMS systems warehouses and different shops in a factory (Ránky, 1986). Materials handling systems is an essential design issue (Chang, et al, 1986), as it pertains to three fundamental functions: loading and unloading of materials, transferring of materials and internal storing of materials.

Flexible manufacturing systems can be classified in terms of the material handling systems that are involved (Groover,1987):

1. In-line
2. Loop
3. Ladder
4. Open-field
5. Robot-centered cell

The in-line type of FMS is a set of workstations literally stationed in-line where jobs come into one end and go out at the other. Stations are typically linked with a conveyor or shuttle system that plays the role of primary material handling system. This system can also be equipped with a secondary material handling system that transfers at workstations to allow back flow on the primary handling system.

The loop type of FMS is basically a conveyor that forms a loop and on which parts flow in one direction. Workstations are stationed around the conveyor with transfer mechanisms that operate as secondary materials handling systems. The ladder type is the basic loop configuration with rungs on which workstations are located. Such systems can be implemented with conveyors or AGVS. The open field type is a combination of loops, ladders, and sidings that constitute a network of workstations typically linked with AGVS. The robot-centered cell type is an FMS where robots are used as the material handling system.

The most common type of materials handling systems encountered in the FMS literature are conveyor systems, AGVS, and industrial robots (Groover, 1987; Ránky, 1986; Modern Material Handling, 1983; Gould, 1987; Tüchelmann, 1986; Stecke and Browne, 1985; Kusiak, 1985; Zisk, 1983; Pierson, 1984; Dupont-Gatelmand, 1982). These systems appear to meet the design criteria necessary for proper FMS operations, namely, 1. random, independent movement of workparts between workstations, 2. the handling of a variety of workpart configurations, 3. convenient access for loading and unloading workparts, and 4. compatible with computer control (Groover, 1987). One type of these MHS is typically used given a particular application. However, it may occur that two of them are combined together in certain cases.

Even though conveyors are found in flow shops and progressive assembly lines, they can also be used in FMS where flexibility is required (Modern Material Handling, 1983). Overhead conveyors, for example are able to manipulate and precisely position parts. Conveyors can handle items in a wide range of shapes and sizes. Table 1 summarizes characteristics of overhead, above floor and in-floor conveyors that can be used within FMS.

Automated guided vehicles (AGVS) are used in low volume and for modular design assembly (Modern Material Handling, 1983). They are well suited for a multi-product, multi-directional backtracking production system (Aneke and Carrie, 1984). Their technical characteristics are the following:

- The path can be programmed and thus modified.
- They can load/unload materials automatically.
- They are computer controlled on a real time basis.
- They can move off the guide path.
- They can lift and store loads to heights at several feet above the ground.

Moreover, the optical path can be modified relatively easily. These characteristics have an impact on the flexibilities associated

TABLE 1. TYPICAL CONVEYORS FOUND IN FMS
(FROM MODERN MATERIAL HANDLING, 1983)

CONVEYORS	DESCRIPTION	FEATURES/LIMITATIONS
Overvead Power/free	Carriers hold parts and move on overhead track.	Flexible routing,live storage,can travel around corners and up inclines..
Trolley	Similar to power and free, but carriers can't move off powered track.	Same as power and free but flexible routing isn't possible without additional equipment.
Above floor Roller /powered	Load carrying rollers are driven by a chain or belt.	Handles only flat-bottomed packages boxes, pallets, or carts.
Roller Gravity	Free-turning rollers	When inclined loads advance automatically.
Skate wheel	Free-turning wheels spaced on parallel shafts.	For lightweight packages and boxes; less expensive than gravity rollers.
Spiral tower	Helix-shaped track which supports parts or small pallets.	Buffer storage;provides surge of parts to machines tools when needed.
Magnetic	Metal bed conveyor with magnitized bed.	Handles ferromagnetic parts
Pneumatic	Air pressure propels cylindrical containers through metal tubes	Moves loads quickly; can be used overhead to free floor space
Car-on-track	Platforms powered by rotating shaft move along shaft	Good for FMS;precise positioning of platforms; flexible routing.
In-floor Towline	Carts are advanced by a chain in the floor.	High throughput; flexible routing possible by incorporating spurs in towline

with the production system. For example, their programmability makes it possible for flexible routing, whereas the optical guidance system (a tape on the floor) affects layout reconfigurability which, in turn, impacts volume and expansion flexibilities. Because of these characteristics, AGVS are used more frequently in FMS (Tüchelmann, 1986) than other types of handling equipment, even though AGVS has been used in applications other than FMS.

Robots, that is electronically programmable servo controlled arms with grippers or other tools, are typically used in high volume production systems or transfer lines (Modern Material Handling, 1983). However, as was noted previously, they are also found in cellular manufacturing, where they control the flow of parts within a cell, which itself is within an FMS. When it comes to automation, robots are used in picking up loads, transferring them between conveyors, stacking and unstacking products from pallets, loading and unloading parts on machines. They can handle and position parts of any shape. They exhibit repeatability, reachability and controllability. They can be programmed, and they have freedom of movement through at least three axes. Again, such capabilities are likely to affect the overall flexibility of the production system.

Other equipment related to materials handling systems are likely to be present in an FMS. Industrial trucks can play a role in the flexibility of a system where tasks cannot be automated economically. They are highly maneuverable to speed operations in tight spaces (Modern Material Handling, 1983). They are used for extra heavy or awkward shaped materials, and in shipping and receiving departments. Also, they are well suited for intermittent plant wide transportation service, and within production areas where moves are infrequent and layout changes are expected (Modern Material Handling, 1983). Other equipment used for material handling which can be found in an FMS are automated storage systems, automatic identification systems, and computers necessary to control material handling systems (Modern Material Handling, 1983).

II-3. FLEXIBILITY INDICES

Much as been written about the concept of flexibility associated with FMS. In this section, variations in flexibility are reviewed, particularly those concerning materials handling systems. Then, previously developed methods for quantifying flexibility as a performance criterion of FMS are described.

II-3.1 THE FLEXIBILITIES ASSOCIATED WITH MHS

Several types of flexibility have been associated with production systems. The list below (Kumar and Kumar, 1987) links flexibility to : 1. the external environment, 2. the inputs , 3. to the process, and, 4. to the outputs:

Flexibilities related to the environment:

- Volume flexibility
- Changeover/parts/product mix flexibility
- Production flexibility
- Job flexibility
- Design flexibility
- Expansion flexibility

Flexibilities related to the inputs:

Material flexibility
Sequencing flexibility

Flexibility related to the process:

Operational adaptability
Rerouting flexibility
Machinery flexibility

Flexibility related to the outputs:

Modification flexibility
Quality flexibility

Operational adaptability can be considered a superordinate goal, that is, a goal of a higher level with respect to other flexibilities, and is less specific than the other flexibilities, as it might include more than one of them. For instance, operational adaptability may include rerouting and machinery flexibilities.

Warnecke, et al, (1986) distinguish between short term and long term flexibility when developing and planning for FMS. Choobineh (1987) defines a *flexibility space* whose components, adaptability, reconfigurability and programmability characterizes a flexible manufacturing system. Stecke and Browne (1985) define flexibilities associated with machining cells and those with material handling systems. They describe a flexibility hierarchy where production flexibility depends on operation, process, product and machine flexibilities on the one hand, and on expansion, volume and routing flexibilities on the other hand. The first four are associated with the machining cells and the last three with the material handling system. They then define an FMS taxonomy and identify the best materials handling system accordingly.

All these flexibilities are concerned with the uncertainty that organizations are facing, and how well they can cope with disturbances originating from the environment (Goldhar and Jelinek, 1985). The inability to respond to changes and disturbances is linked to opportunity costs incurred from the system. Such costs form a basis that will be used in generating measures or indices of flexibility.

A fundamental question regarding flexibility is how much is enough (Jones, 1987; Modern Material Handling, 1987) ? Given a certain level of uncertainty in the environment, what is the optimal amount of flexibility that a system should have ? Too little flexibility will cause the system to incur opportunity costs in terms of lost sales and other costs resulting from poor responses to market disturbances. Too much of it might result in over investment in expensive automated systems that are simply not needed for the organization to satisfy its market. The first step in addressing this issue is to quantify flexibility.

II-3.2 THE VALUE OF FLEXIBILITY

Several measures and indices have been proposed for quantifying flexibility. Webster and Tyberghein (1980), for example, argue that job shop flexibility can be estimated by layout reconfigurability costs necessary to respond to changes in product mixes and volume. Zelenovic (1982) links the complexity of a production system with its effectiveness in terms of time needed for the system to adapt to new job task. Kumar and Kumar (1987) express the idea that flexibility should be associated with how well a system can cope with uncertainty or lack of information about the environment. Along this line of thought, they suggest entropic measures of flexibility. These measures are functions of the number of options available to an organization. The higher this number, the higher is the flexibility for this system.

Other studies have attempted to evaluate the worth or value of flexibility. Park and Son (1987), define flexibility in terms of opportunity costs of a system not being able to respond to changes. They develop *partial* and total flexibility measures according to the following factors: the opportunity costs of equipment under utilized, setup costs, waiting costs, and inventory costs. The idea behind this study is that the overall flexibility of a system can be conceptually decomposed into components and can be *added* together to get what is called total flexibility. Each of these costs constitute the basis for the following partial flexibility measures:

Equipment flexibility:

$F_E = O_T/C_I$,
where O_T is total output,
and C_I is idle cost ($) for equipment .

Product flexibility:

$F_P = O_T/A$,
where A is setup cost.

Process flexibility:

$F_S = O_T/C_W$,
where C_W is the cost of parts processed.

Demand flexibility:

$$F_D = O_T/H,$$

where H is inventory costs of finished products and raw materials.

Total Flexibility Measure:

$$T_F = O_T/(C_I + A + C_W + H).$$

Similar measures were also developed for quality and productivity, and were integrated into a single performance criterion. All these measures were then used as variables in a simulation of a small FMS in order to examine the possible relationships between productivity, quality, and flexibility.

Another simulation study was done (Hutchinson and Holland, 1982) in order to quantify the (relative) value of flexibility of an FMS with respect to a transfer line. Their study was based on the assumptions that flexibility could be defined in terms of: 1.the ability to reduce overcapacity charges by more closely matching capacity to demand, 2. the reduction of long term capital requirement through capacity conversion, and 3. the short term conservation of capital through the incremental acquisition of capacity. The idea behind this study is that flexible manufacturing systems have a distinct competitive advantage with their ability to "... incrementally acquire production capacity, to simultaneously process many types of parts, and to convert production capacity" (Hutchinson and Holland, 1982).

A study regarding assembly systems uses economic variables that can be related to flexibility of these systems (Boothroyd, 1982). Parameters such as the number of parts in the assembly, annual production volume per shift, product style variation, design changes, and number of products to be assembled are included in the model so as to determine the best among manual, special-purpose automatic, and programmable assembly systems.

A more extensive study based on Boothroyd's (1982) has been done by Miltenburg and Krinsky (1987) that compares five types of assembly manufacturing systems: 1.manual assembly, 2.manual assembly with mechanical assistance, 3. indexing and buffered lines with special purpose workheads, 4. transfer machine with robot workheads, and 5. robot assembly cells. They use a financial model that combines economic and technical variables pertaining to each particular system. An interesting feature of their model is their attempt to imbed computations in a decision process that includes four phases: 1. the deterministic phase, 2. the probabilistic phase, 3. the informational phase, and, 4. the decision phase, where it is determined if the available information is sufficient to choose an alternative, or if an information gathering process is needed. Their model includes variables such as the number of different assemblies to be manufactured in year t, the total market size for assembly i in year 1, assembly time for each part, plant efficiency , part quality, etc. The performance criteria are basic economic measures such as the net present value (NPV), the annuity equivalent (AE), the internal rate of return (IRR), and payback. Their model makes provisions for stochastic aspects coming from the uncertainty of certain variables. This is done by estimating cumulative density functions for each of them. The cumulative function of the annuity equivalent is then estimated from all the possible combinations of the variables that are considered to be stochastic. Stochastic dominance is then used to rank alternatives. If alternatives are not dominated, then certainty equivalents are computed for each alternative (based on a presumably defined utility function of the decision maker). Finally, the cost of new information is computed to establish if it is worthwhile to search for new data pertaining to the alternatives.

Other studies of flexibility have been tied to FMS scheduling, loading and operational planning. They include measures that are closely related to detailed aspects of the FMS design and planning and typically uses mathematical based models such as linear programming and queuing networks.

Greene and Sadowski (1983), in their study of cell loading and scheduling, propose flexibility indices that are related to manufacturing cells. They define a *machine density* index which measures the variety of machine types within cells; this index is defined on a zero one scale. A machine density of zero means that cells have one type of machine (exclusive to all other cells); a machine density of one means that cells contain all machine types. The higher the variety of machines within cells, the more flexible is the manufacturing system. They also define *job density* which is the proportion of cells that can perform the required jobs. If job density is equal to zero, then each cell can process one job only. If it is equal to one, then all jobs can be processed on all cells. Again, the greater this index, the more flexible is the manufacturing system.

However, as Buzacott (1983) points out, the *overall* flexibility of a system can be achieved by having low flexibility at the machine level while having high flexibility at the system level (that is by increasing the variety of routes jobs can take through the system). In other words, "...specialized machines require flexibility at the system level to give overall flexibility, while general purpose machines do not require much system level flexibility for [a given] overall flexibility ". This would suggest that materials handling systems can thus increase the flexibility of a manufacturing system for a given flexibility index at the machine or cell level.

A study by Sarin and Dar-El, (1985), has attempted to integrate some of the above flexibilities in the development of a linear programming based scheduling model. They define a generalized concept of flexibility by using a four level hierarchy: part mix is at the top level indicating that one part can be processed by more than one operation set (the second level). One operation set can, in turn, have more than one feasible sequence (the third level). Finally, one feasible sequence can be routed differently on the available machines. This analysis suggests that types of flexibilities may not be totally independent of each other as one permits another. Again, materials handling systems seem to play an important role as they make possible routing flexibility (which itself is partly defined in terms of the other types of flexibilities).

Talaysum, et al, (1986) propose new production functions that include economies of scope. This aspect of FMS will be discussed further in another chapter. According to them, those economies of scope prevail over traditional economies of scale, especially in the presence of product differentiation and when operations costs of multi-purpose machines are lower than those incurred by specialized machines. According to these authors, economies of scope come from:

1. The fact that "... design and process control information encoded in software has the attribute of a public good." (Talaysum, et al, 1986). This means that in a computerized manufacturing

environment, information is easier to "modify" than physical systems.

2. The fact that flexibility of the machines themselves can be used in balancing production and demand. In this particular case, a flexible machine that has been used for a particular product, A, can be used in manufacturing another one, B, if demand exceeds the capacity of other machines (which were responsible for producing B). This has the effect of reducing in process or finished good inventories.

3. A better use of materials. A CIM environment has the ability to reduce scrap and wastage.

4. Labor costs. In this case, labor (in large part a fixed investment) will be used in designing a FMS configuration producing a range of products. " Since these versions (of these products) would have various degrees of commonality in R & D, design , process control, and equipment specification inputs, giving rise to economies of scope, it would be advantageous to extend the number of feasible target markets that can be captured by increasing the variety of the plant output" .

It would probably be very difficult to estimate such a production function that would reflect all of the above economies of scope. It would seem more appropriate to attempt to measure flexibility. As the authors say: " Clearly, efforts aiming at defining the number and the identities of product varieties which will yield the minimum unit production are doomed to futility. Rather than defining which specific varieties should be included in the new plant, it is both more feasible and more congruent with the operational characteristics of the CIM plant to define the long-run production decision as one of choosing the degree of flexibility of the production systems which determines the feasible extent of product differentiation" (Talaysum, et al, 1986).

Carter (1986) has proposed a conceptual framework for all types of flexibilities which are classified in terms of time frame and incentives. Time frame is a dimension that goes from the very short term to the long term, whereas incentive is a criterion that justifies the importance of flexibility. In this case, justification can be a strategic level, an economical level or a security (incentive) level. For instance, routing flexibility falls within the very short term (time frame) and is basically used as an insurance mechanism. Expansion flexibility is for medium to long term, and its implication for the organization is strategic.

Mandelbaum and Buzacott (1986) attempted to lay the theoretical foundations for the integration of flexibility within a stochastic environment. They develop a theoretical model that includes the number of products, n, that a manufacturing system can produce . They set their model in an uncertain environment. However, the probability distribution of these outcomes (in terms of losses to the firm) is assumed to be known. A two stage decision process has to be performed by the decision maker: Which manufacturing system to install, and what are the products to be manufactured by the chosen system ? In this framework, the decision maker has two alternatives: building a manufacturing system that produces one product or one that produces n. Then he chooses the product that he can manufacture with this system. By assuming that these losses (which could be considered here as opportunity costs) are uniformly distributed over the same parameters α and β , then they are able to derive an expression of the expected loss as a function of the uncertainty parameters α and β and n. It can be seen from this function that as n increases, the expected loss decreases, and that as the uncertainty increases, it becomes advantageous to invest in more flexibility (n).

Afentakis (1986) develops flexibility indices within a model for layout design in FMS using a graph approach. In this particular research, the layout problem is defined in terms of machine disposition and links (material handling system). An optimal layout design is one where : "... machines must be connected in a way that the number of transfer links used is minimized, the traffic between machines is kept as low as possible, and the flexibility of the system is preserved. ".

Afentakis defines two flexibility indices:

Layout flexibility:

$$r_l = \sum_{i \in M} R_i / m^2$$

where m is the number of machines belonging to set M, and where R_i is the set of machines that machine i reaches in a graph defined in terms of the material handling links which are represented by arcs, and machines by nodes. Hence, a ratio r_l equal to 1 means that the layout is totally flexible as each machine can reach any other machine.

System flexibility:

$$r_s = \sum_{p \in P} x_p / n$$

where x_p equals 1 if there is at least one feasible routing for part p and 0 otherwise (where P is the set of parts). This index measures the percentage of parts that can be manufactured by the system. An alternative measure of system flexibility is proposed by Afentakis as:

$$r_t = \sum_{p \in P} (y_p / n_p) / n$$

where y_p is the number of feasible routings for part p, and n_p is the total number of routings for that same part.

The design problem, according to Afentakis is to find a layout graph that includes the machines involved in the production of parts, and for which there is exactly one simple path from machine i to j (in other words, the flexibility of the layout must be one). Another design criterion is that the costs of this layout (represented by the cost of each link) be minimized. The author then proposes a heuristic procedure for determining the most desirable layout.

II-4 MULTI-CRITERIA APPROACHES

The problem of evaluating alternatives subject to more than one criterion may be tackled in several ways. Among the available approaches within the realm of multiple criteria decision making, one can use multiattribute theory, compromise programming, goal programming, linear multiobjective programming, the displaced ideal model, and the analytic hierarchy process (Zeleny, 1982; Saaty, 1980). The last two approaches, (which will eventually be combined together) the analytic hierarchy process (AHP) and the displaced ideal model (DIM), are described below. They have been chosen because of their ability of deal with complex problems where several variables are involved and when interactions among them are present. The AHP is a methodology that decomposes a large problem (too difficult to tackle directly) into subproblems that can be handled more easily. This technique can allow for more than two levels of analysis, since a superordinate goal can be broken down into lower level objectives which can themselves be decomposed into subobjectives, etc. The AHP is thus able to link operational aspects or variables pertaining to material handling systems with strategic considerations. For example, one flexibility may be more important in the face of strategic goals of the firm (quality, response time...).

The displaced ideal model is part of what Hwang, et al, (1980) call interactive methods or methods where articulation of preference information is given progressively as the decision maker moves into the analysis of available alternatives. According to the taxonomy of these authors, multiple attribute decision making techniques can be classified in terms of when preference information is given: before the optimization process (a priori articulation of preference information), during the optimization process (progressive articulation of preference information) or after the optimization process (a posteriori articulation of preference information). Multiattribute utility functions are an example of an a priori preference information technique. In this case, the utility function (which has to be specified prior to the analysis) is given to the analyst, who then performs the optimization process. Methods where preference information is given progressively are essentially interactive. They are used "...for complex problems when the decision maker is unable to indicate preference information ... but for which he is able to give preference information on a local level to a particular solution" (Hwang, et al, 1980). The advantages of this type of approach are:

- No a priori preference information is needed.

- It is a learning process for the decision maker to understand the behavior of the system.

- Only local preference information is needed.

- Since the decision maker is part of the solution process, the solution obtained has a better prospect of being implemented.

- There are less restrictive assumptions as compared to other types of methods (utility functions , constraints).

In particular, the displaced ideal model is a technique that is closer to the decision making process as it permits *partial decisions* within the analysis or decisions made on a small set of alternatives. It is also a technique that can quickly tell the decision maker how close each alternative is to an *ideal* (which is defined in terms of the current alternatives) .

The displaced ideal method will be able to start the analysis of material handling systems on a small set of alternatives, so that trade offs between flexibilities may be assessed more easily. The solution space will then be extended as understanding of these systems progresses. Another advantage of the displaced ideal model is that it can be integrated with the AHP, since both of them deal with local priorities and include solution spaces that are discrete, such as a set of material handling systems. Finally, all quantitative data are transformed in a common *closeness* scale which will make possible the integration of the flexibility indices (which constitute a surrogate measure of opportunity costs when aggregated) with more tangible costs (first and operating costs).

II-4.1 THE ANALYTIC HIERARCHY PROCESS

The analytic hierarchy process (AHP) is a mathematically based multi-criteria decision methodology that draws from systemic concepts and from behavioral considerations. It attempts to analyze a system to the extent possible by forcing the decision maker to decompose the problem into sub problems, which, in turn, are broken down into smaller clusters of elements. The methodology can be applied to problem solving, design, planning, investment evaluation, cost benefit analysis, prediction, conflict resolution, marketing and optimization (Saaty, 1980; Saaty and Kearns, 1985; Wind and Saaty, 1980; Saaty, 1986a; Saaty, 1986c). This approach has been shown to have important ramifications in decision theory, especially concerning utility functions and expected value theory (Hughes, 1986; Saaty, 1986d). The AHP has been combined with other approaches such as multiobjective linear programming problems (Arbel and Oren, 1986), the surrogate worth trade-off method (Debeljak, et al, 1986) and goal programming (Olson, et al, 1986) to produce more comprehensive multi-criteria decision methodologies.

The AHP appears to be very versatile, as it can be used as a group process or at the expert level mode. Several criteria can be integrated from one level to another. It can be used as a multi-time planning method, i.e., dynamic aspects of variables that evolve through time can be included in the model. Finally, both qualitative and quantitative data can be used simultaneously within the same problem.

Another important aspect of the AHP is that even though it is concerned with hierarchies, it can also deal with more complex systems exhibiting feedback and interdependencies within their components. In fact, hierarchies, as described in this methodology, are considered as particular networks where links between elements go in one direction only (namely, from top to bottom).

II-4.1.1 An Overview

The AHP can be best summarized by its three underlying principles or ideas (Saaty and Kearns, 1985): 1. identity and decomposition, 2. discrimination and comparative judgement, and 3.synthesis. The first principle deals with breaking down a problem or a performance criterion into sub-criteria which form a level that can be said to be below its superordinate goal. As one goes down the hierarchy, the clusters of elements become "smaller" and more manageable. At the bottom of the hierarchy are typically possible actions, alternatives (typically mutually exclusive) available in the attainment of the overall goal, or constitutive elements of the system or focus under consideration (See Figure-1.a and b). Thus, the problem is modelled in terms of levels and sub-levels where a sub-level *depends* on the level immediately above for the evaluation of its elements. This concept of dependence will be formalized later. Once the system or problem as been properly defined and its hierarchy completed, each element within a cluster or level has to be ranked with respect to each element belonging to the level above. The second principle, discrimination and comparative judgement, is used at this point. Each element is compared to every other element in a pair wise fashion in terms of their relative importance with respect to one of the elements of the level above. Each of these comparisons are put into a matrix whose components, a_{ij}, are equal to w_i/w_j , which is the ratio of the weight of element i over the weight of element j. Such a matrix is developed for each element of the current level in the hierarchy. From each

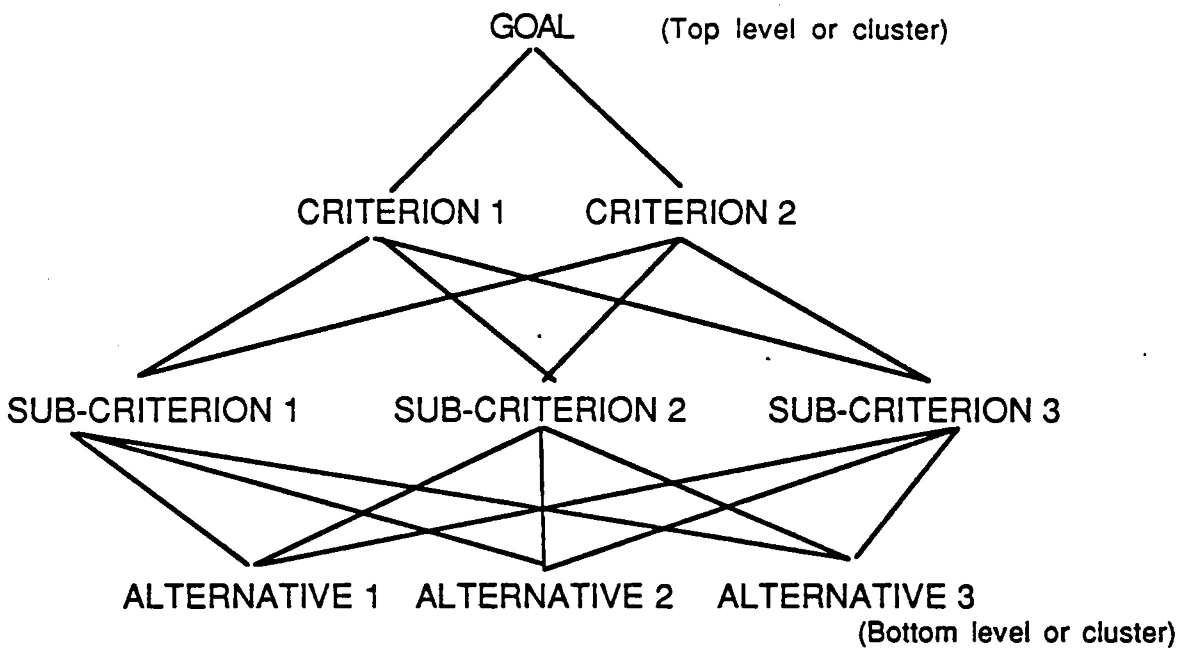


FIGURE -1.a EXTENDED FORM.

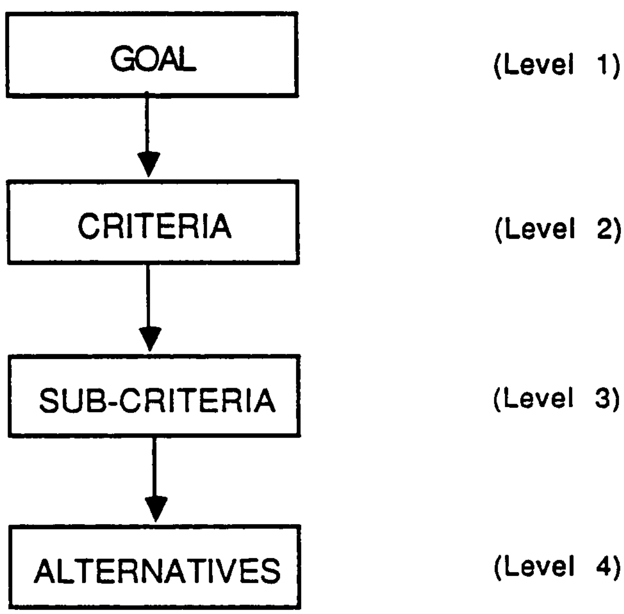


FIGURE 1.b CONDENSED FORM.

FIGURE.1.REPRESENTATION OF A HIERARCHY.

of these matrices are extracted priorities that rank the elements of one level with respect to an element of the above level. There are several computational methods to derive these priorities (Saaty, 1980; Fitchner, 1986; Zahedi, 1986). The one that seems to be the best is the right eigenvector method in which the normalized eigenvector associated with the largest eigenvalue of the comparison matrix is computed. The eigenvector method is preferred as a ratio scale over other simpler methods, because it allows for some inconsistencies on the part of the decision maker when building the comparison matrix (Saaty and Takizawa,1986; Vargas,1986). Other advantageous characteristics of this eigenvector method are, 1.unique scaling of preferences, 2. consistency with utility theory (a utility function can be built from the eigenvector weights), 3. these weights are stable under small perturbations of the pairwise comparisons, 4. the associated eigenvalue of the largest eigenvector is a measure consistency of preferences of the decision maker (Saaty, 1980, Vargas, 1986). This eigenvector expresses *local priorities*, that is, priorities associated with one level only. Eventually, these vectors are combined together, so that overall priorities of the elements of the lowest cluster with respect to the top goal or performance criterion can be known. Finally, after all these vectors are computed, then they are multiplied together from the bottom of the hierarchy to the top to get composite priorities that express overall priorities of the bottom elements with respect with the top level in the hierarchy.

Figure 2. depicts the computations necessary in order to reach these composite priorities. The matrix A of pairwise comparisons is reciprocal $(A_{ij} = A_{ji})$. The eigenvector of A is associated with the largest eigenvalue of A and is normalized to one.

More formally, each vector of one level can be put together to form a matrix W_{IJ} whose columns are the eigenvectors themselves,

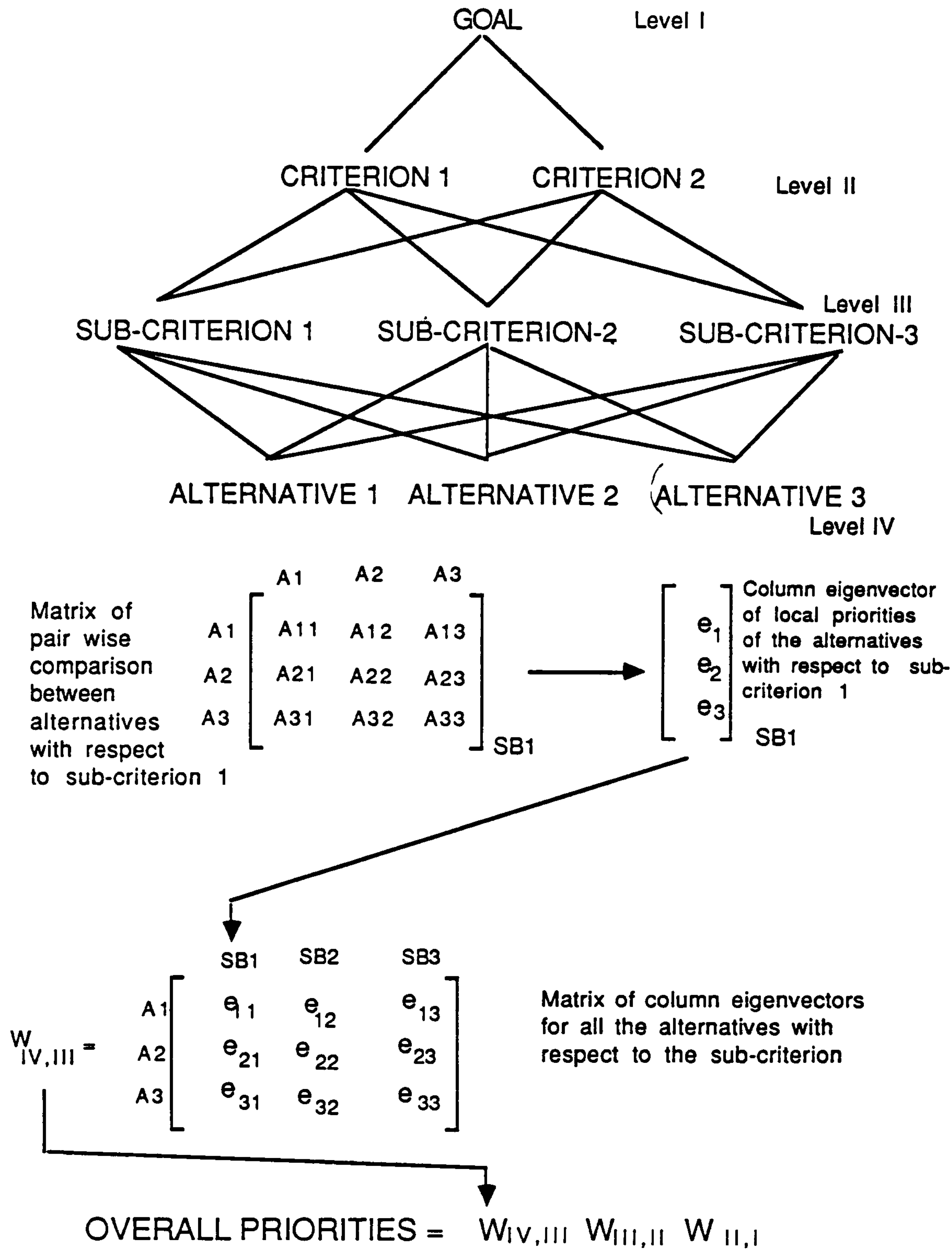


FIGURE 2. THE AHP FOR A PURE HIERARCHY

expressing priorities of the elements of level I with respect to the elements of the above level J. If there are N clusters or levels in the hierarchy, then the overall priority of the elements of the Nth (or bottom level) with respect to the element(s) of the first or top level is the following matrix product:

$$W_{N,N-1}W_{N-1,N-2} \cdots W_{32}W_{21}\,.$$

Each of the above matrices W_{IJ} are constructed in the following way. Assuming that level I is below J in the hierarchy, then each column is an eigenvector (normalized to one) representing the local ranking or priority of all the elements of I with respect to each element of J. Thus, the first column of W_{IJ} is the ranking of the elements of I with respect to the first element of J. If there are n elements in I and m in J, then W_{IJ} will have dimensions n*m (See Figure 2.).

II-4.1.2 Axiomatic Foundation

An axiomatic foundation of the AHP can be found in Saaty, (1980) and Saaty, (1986b). The methodology is based on the ideas of derived scales that are built from fundamental scales, and used to compute composite scales.

A fundamental scale can be defined as a function (P_C) that assigns a positive number to every pair, A_i and A_j , of elements of a cluster for each element (or criterion C) of another cluster. By definition,

$$A_i > A_j \quad \text{iff} \quad P_c(A_i, A_j) > 1$$

$$A_i \sim A_j \quad \text{iff} \quad P_c(A_i, A_j) = 1,$$

(the ~ indicates indifference between alternatives)

As an axiom,

$$P_c(A_i, A_j) = 1/(P_c(A_j, A_i))$$

And, as a definition of consistency for the mapping of P_c,

$$P_c(A_i, A_j)P_c(A_j, A_k) = P_c(A_i, A_k).$$

If the above condition does not hold, then the mapping is said to be inconsistent. Whether or not the function P_c is consistent, a derived scale can be defined that uses the relative dominance between the A_i and A_j, and determines a local ranking (with respect to an element c of another cluster) for all the A's in a cluster or level. In this sense, a derived scale is a mapping between two numerical relational systems.

For each element c, a vector of these local priorities is derived and are put together to form a matrix. Such matrices are thus defined for each pair of levels or clusters, so that local priorities or local weights can be multiplied to arrive at a global ranking of the elements belonging to the lowest level in the hierarchy.

II-4.1.3 The Concept of Hierarchy

The concept of hierarchy is fundamental in systems theory as it clarifies both structure and functions of a system, and as it permits a sound understanding of a complex problem. Advantages of hierarchies are the following (Saaty, 1980):

(1) Hierarchical representation of a system can be used to describe how changes in priority at upper levels affect the priority in lower levels.

(2) They give great detailed information on the structure and function of a system in the lower levels and provide an overview of the actors and their purposes in the upper levels.

(3) Natural systems assemble hierarchically, i.e., through modular construction and final assembly of modules, evolve much more efficiently than those assembled as a whole.

(4) They are stable and flexible. Stable in that changes have small effect, and flexible in that additions to a well-structured hierarchy do not disrupt the performance (Saaty, 1980).

A formal definition of a hierarchy follows from the ideas of outer and inner dependence. Outer dependence is defined between clusters (or levels) while inner dependence is concerned with elements within a particular cluster. Cluster B is outer dependent on A, if a fundamental scale can be defined on B with respect to every element in A. Both of these dependencies are referred to as *functional* dependencies, in contradistinction to *structural* dependencies which will be described later. A hierarchy can be considered to be a network of a special kind with outer dependence *in one direction* , that is from bottom to top. It is basically a graph with no cycles.

II-4.1.4 The Concept of Networks

The AHP approach has been especially designed for hierarchies, but it can also deal with more complex structures where dependence is not in one direction. Two types of such *non linear* relationships can be found in a network: feedback and inner dependence.

Feedback is simply outer dependence going upward in a hierarchy (Hämäläinen and Seppäläinen, 1986). Figure 3. shows a hierarchy with feedback where the goal (or goals) *depends* on the alternatives. The network in Figure 3 can describe the case where the existing alternatives (for example, investments in production systems) have an effect on the relative importance of the goals, which could be sub-divided in terms of short and long term goals. In effect, the fact that these investment alternatives might, for example, be very expensive, may influence the decision maker in giving more weight to long term consideration.

Inner dependence expresses the fact that elements within a cluster are dependent among themselves with respect to elements of another cluster. In other words, there is inner dependence when "...the elements of a set are on the one hand outer dependent on a second set, and on the other conditionally dependent among themselves with respect to elements of the second set which serve as attributes" (Saaty and Takizawa, 1986).

In Figure 4, inner dependence is illustrated. In this case, the sub-criteria are dependent upon themselves (with respect to one or more criteria). From a more practical point of view, inner dependence would be represented by horizontal arrows (pointing from one element to another) within a level of a hierarchy. Saaty and Takizawa (1986) describe an application where the goal of a hierarchy is to find the functional dominance of a motorcycle's parts. The criteria are four basic functions: stop, turn, run and accelerate. The alternatives are the six main parts, namely the brakes, steering, body frame, engine, wheels, and suspension. Usual outer dependencies between alternatives and criteria, and between

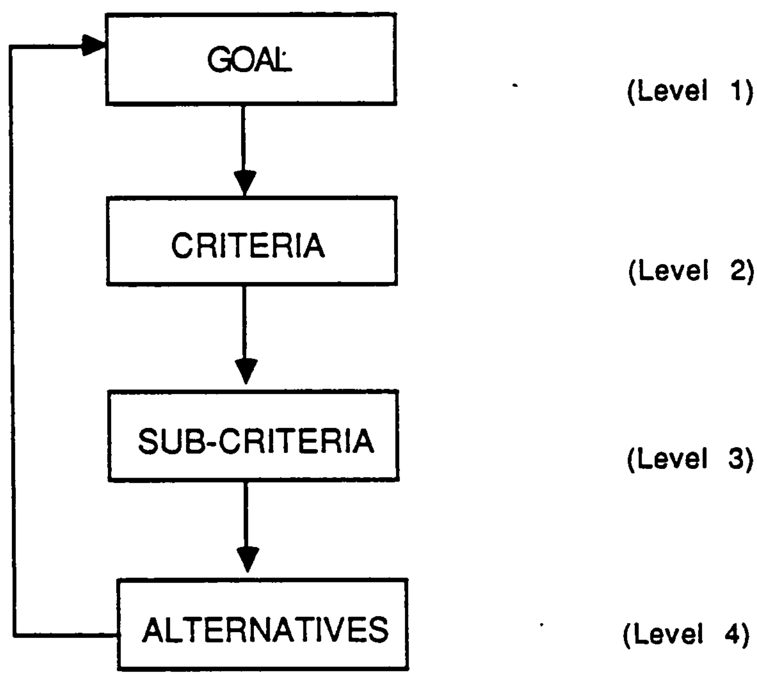


FIGURE.3 HIERARCHY WITH FEEDBACK

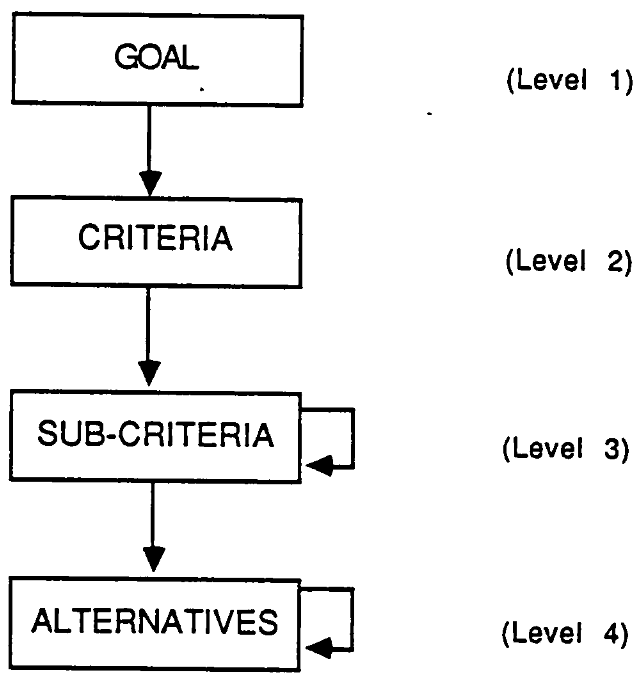


FIGURE.4. HIERARCHY WITH INNER DEPENDENCE
(DEPENDENCE WITHIN A CLUSTER)

criteria and the overall goal, are defined and computed. But in this case, inner dependencies exist between functions. For instance, the function turn may be influenced by the function stop, i.e., one must first slow down before turning. In other words, stopping is not only used for bringing the motorcycle to a rest, but also for slowing down in a curve. This additional effect must be accounted for. On the other hand, the function stop has no effect on running or accelerating the motorcycle.

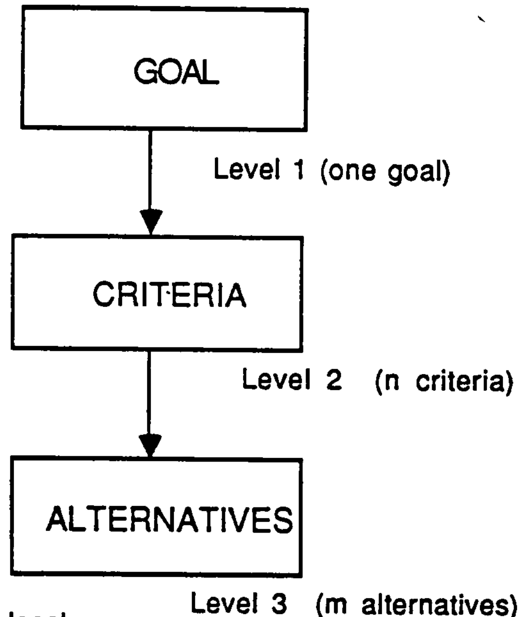
Another example of inner dependencies may be found in the flexibility hierarchy developed by Stecke and Browne, (1985) where the overall system flexibility is broken down into two sets of intermediate flexibilities (one for machining cells and another for the MHS) and in terms of basic flexibilities (namely machine and routing flexibilities). At the intermediate level are volume and expansion flexibilities associated with materials handling systems. Volume flexibility is the ability to operate an FMS at different production volumes, whereas expansion flexibility is the ability of an FMS's layout to be expanded. In section 1.3, it was suggested that these flexibilities might be in conflict with each other. However, it might be the case that in some ways there are positive interaction among them. For instance, volume flexibility results presumably form the ranges in speed and capacity of the materials handling system. However, volume flexibility may also be achieved by expanding the FMS itself. Therefore, expansion flexibility may have an effect on volume flexibility (in the sense that it contributes to another flexibility at the same level in the hierarchy). Volume flexibility, in turn, may have an effect on routing flexibility. Recall that routing flexibility is the capability of a system to reroute one or more jobs due to machine breakdown. The possibility of rerouting a job depends on the ability of the remaining machines or cells to absorb the increasing throughput. If volume flexibility of the material handling system is not sufficient (presumably due to lack of speed or capacity), then rerouting will not be possible. The performance of the overall system will go down as it cannot meet demand. Therefore, increasing volume flexibility of a MHS appears to improve its capability of dealing with internal disturbances of the production system as rerouting becomes more feasible.

For the case of networks, the computation of composite priorities is more involved. The procedure is to first analyze the system or problem as if it were a pure hierarchy (with no dependence) and compute the usual local priority matrices between clusters, or as they are called, matrices of local independence vectors. If, for example, the problem is described by two clusters A and B, where B is outer dependent on A, and where A is also outer dependent on B (that is, there is feedback from B to A), then two matrices of local independence vectors are computed. They are then placed in what is called a *supermatrix* which is raised to successive powers in order to obtain block matrices of *limiting priority vectors,* describing the overall impact or long term effect of each element of a cluster on the elements of the other. An example of such a supermatrix is shown for a pure hierarchy in Figure 5 and for a two level system with feedback in Figure 6.

In the case of inner dependence within a cluster, the usual matrices (W_{IJ}) cannot be used as such, but have to be combined with the effects resulting from inner dependencies within a cluster. These modified W_{IJ} are called *interdependence* matrices (and might be noted $(W_{IJ})^{INTER}$). The procedure in this case is somewhat more complex.

First of all, the W_{IJ}, which are called matrices of local independence vectors are computed for each outer dependence relationship (as if there were not any inner dependencies) in the

$$S = \begin{array}{c} \\ G \\ C \\ A \end{array} \begin{array}{c} \begin{array}{ccc} G & C & A \end{array} \\ \left[\begin{array}{ccc} 0 & 0 & 0 \\ W_{21} & 0 & 0 \\ 0 & W_{32} & I \end{array} \right] \end{array}$$



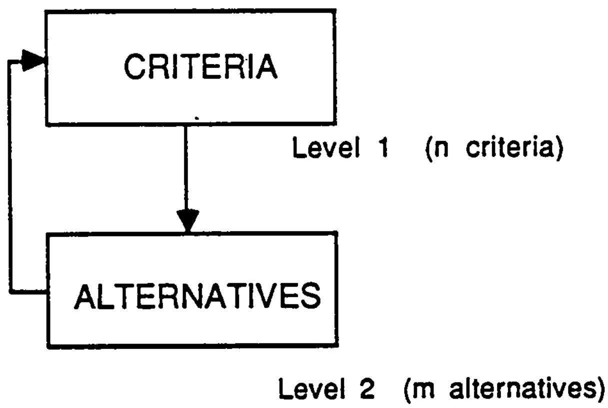
W_{21} matrix of column eigenvectors giving local priorities of the criteria with recpect to the goal (n *1)

W_{32} matrix of column eigenvectors giving local priorities of the alternatives with respect to each criteria (m*n)

The overall priorities of the alternatives with respect to the goal are given by the product of W_{32} and W_{21} which gives a column vector (m*1).

FIGURE 5. SUPERMATRIX (S) ASSOCIATED WITH A PURE HIERARCHY (WHERE THERE IS ONE GOAL, N CRITERIA AND M ALTERNATIVES)

$$S = \begin{array}{c} \\ C \\ A \end{array} \begin{array}{c} \begin{array}{cc} C & A \end{array} \\ \left[\begin{array}{cc} 0 & W_{12} \\ W_{21} & 0 \end{array} \right] \end{array}$$



W_{21} matrix of column eigenvectors giving local priorities of the alternatives with respect to each criteria (m*n)

W_{12} matrix of column eigenvectors giving local priorities of the criteria with respect to each alternatives (n*m)

Limiting priorities are given by raising S to powers

FIGURE 6. SUPERMATRIX (S) ASSOCIATED WITH A FEEDBACK SYSTEM (WHERE THERE IS N CRITERIA AND M ALTERNATIVES).

network or hierarchy. Then, *dependence* matrices are computed to take into account inner dependencies within a cluster. They are constructed from pairwise comparisons matrices. The question here is"...given an alternative and an attribute, which of two alternatives influences the given alternative more with respect to the attribute, and how much more than another alternative ?" (Saaty and Takizawa, 1986). These dependence matrices are multiplied with the appropriate column vectors of the local independence matrices, so that matrices of *interdependence* vectors can be put together to obtain the combined effect of outer and inner dependence. Finally, these interdependence matrices, $(W_{IJ})^{INTER}$, are multiplied together to get final composite priorities.

II-4.1.5 Application to MHS

The AHP has been used in evaluating new manufacturing technologies. One model (Sullivan, 1986) compares a traditional job shop against a FMS by using a cost benefit approach where the benefits hierarchy includes strategic operational aspects at the first level, and performance criteria such as quality, market response and flexibility . In an other model (Arbel and Seidmann, 1986), more extensive hierarchies are developed for comparing FMS's together. The benefits hierarchy is composed of six levels where overarching performance criteria such as economic, production, and organizational aspects are integrated with specific technical parameters pertaining to the proposed FMS's. The costs hierarchy includes costs associated with system acquisition (installation and service) and system dependability (vendor and operational integrity). A third model has been applied to material handling systems comparing AGVS, fork trucks and monorails with respect to flexibility, maintainability, compatibility, safety and ROI (Frazelle, 1986).

II-4.2 THE DISPLACED IDEAL MODEL

This technique, as with the AHP, deals with the problem of choosing the best (the most preferred) alternative when several attributes are involved. However, this approach is more appropriate for attributes that can be quantified and better reflects the dynamics of the decision making process.

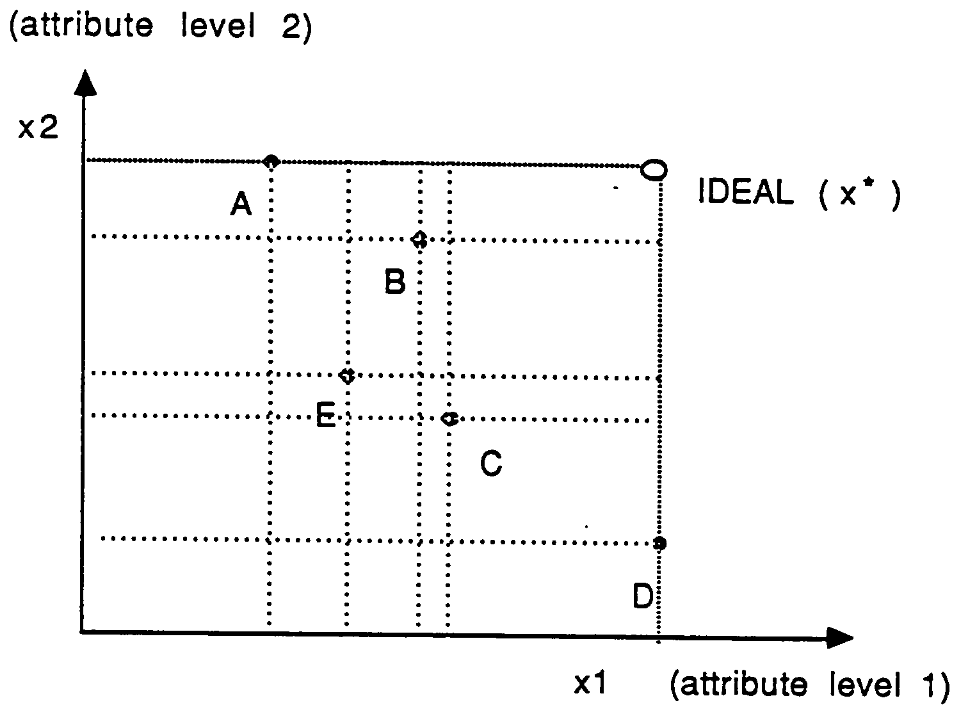
The other main advantage of this technique is that it takes into account structural dependencies between alternatives and attributes. Dependencies of that kind arise when the ranking of alternatives with respect to the overall objective changes when one additional alternative is included, or when one current alternative is deleted from the set.

The approach is based on the concept of an *ideal alternative* defined in terms of the current set of possible alternatives which are associated with some attributes. More specifically, suppose that m alternatives are to be compared to each other using n attributes. Let x^k be the *k*th alternative and, x_i^k be the level of attribute i attained by alternative k.

Therefore, each alternative x^k is defined in terms of a vector whose components are the x_i^k. The ideal point, x^* is defined in terms of its components, x_i^* in the following way:

$$x_i^* = \underset{k}{\mathrm{Max}}\ (x_i^k)\ ,\ i=1,2\ ..,\ n.$$

Figure 7 illustrates how this ideal point is defined. It can be seen that by adding or deleting an alternative the position of the x_i^* is likely to change. The fact that the ideal point can be modified that way signals the presence of structural dependence. In



A, B,C, D, are non dominated alternatives
E, is a dominated solution

FIGURE 7. THE CONCEPT OF THE IDEAL ALTERNATIVE
(ADAPTED FROM ZELENY, 1982).

other words, the ranking of the alternatives (with respect to the ideal point) may change as a result of modifying the set of available alternatives.

Figure 7 also illustrates the concept of Pareto optimality. Alternatives A, B, C,and D are non dominated with respect to the two attributes X_1 and X_2 ; these alternatives settle the boundaries of the Pareto frontier along which an increase in one attribute corresponds to a decrease in the other (from B to C for example). Alternative E, however is dominated, since at least one alternative (B) is superior in terms of both attributes. Dominated alternatives are not to be discarded in this approach, because they provide for second best solutions, that is solutions nearly as close to the ideal as non dominated solutions.

The ranking of the alternatives is computed by maximizing the following function:

$$L(\lambda,k) = \sum_i \lambda_i d_i^k ,$$

where λ_i is the weight of attribute i (presumably with respect to an overall goal), and d_i^k the degree of closeness of alternative k with respect to ith component, x_i^* , of the ideal alternative x^*. The closeness function may be defined thus:

$$d_i^k = (x_i^k)/(x_i^*),$$
$$\text{where} \quad 0 \leq d_i^k < 1.$$

The weights, λ_i (or *attribute attention levels*) can be determined in several ways, one of which is the AHP. However, according to Zeleny, (1982) these weights should also reflect the *amount of information* transmitted by the scores of alternatives with respect to the ith attribute. If the alternatives are all the same with respect to a given attribute (given attribute i, the x_i^k are equal for all k), then this attribute should have very low weight, since it does not discriminate between the current alternatives. Another attribute would be used to rank them. In other words, the way alternatives are scattered in the attributes space should have an effect on the weights of the attributes themselves. This is another form of structural dependency.

Zeleny (1982) proposes the following computation for the overall weights λ_i:

$$\lambda_i = \beta_i * \omega_i,$$

where the ω_i are called a priori attribute importance with respect to some superordinate goal and may be computed using the AHP. The β_i are context-dependent weights reflecting the informational importance of a given attribute and depend on the particular set of alternatives as they are computed using a *contrast intensity* function that involves the d_i^k (Zeleny, 1982):

$$\beta_i = (1-e(d_i))/(n-E) .$$

Where $$e(d_i) = (1/\ln(m))* \sum_{k=1}^{m} (d_i^k/D_i)\ln(d_i^k/D_i),$$

$$E = \sum_{i=1}^{n} e(d_i),$$

$$D_i = \sum_{k=1}^{m} d_i^k \quad \text{for } i = 1, \ldots n$$

m: the number of alternatives

n: the number of attributes.

The main hypothesis of the displaced ideal model is that the decision maker will choose the alternative that is the *closest* to the ideal. According to Zeleny (1982), "...to be as close to the perceived ideal as possible is then identical with confidence maximization and thus constitutes an operational criterion for deciding when the "best" solution has been achieved." The displaced ideal model is also a *process* where the decision maker modifies the solution space by deleting or generating alternatives until he estimates that a particular alternative is close *enough* to the ideal alternative.

Other characteristics of such an approach is that there is progress toward an ideal goal or solution. It forces a search process that generates alternatives that get closer and closer to the ideal. In this sense , it is not short term oriented.

This research proposes decision frameworks which would include computerization of different aspects of the decision process, partly described in section II-5, in view of creating a manufacturing tool for material handling systems. This decision support system should, among other things, be built upon the principles underlined by the AHP and the displaced ideal model. These two multi-criteria decision making techniques would help in designing a DSS that is more *process independent* and user driven and is thus closer to the decision maker. By being process independent, a DSS would not lock the decision maker into rigid and specific steps and would support a more creative and efficient thinking process (Sprague and Carlson, 1982).

II-5. ANALYSIS OF FMS

Design criteria have been suggested by Suri,(1986), for the implementation of analytic models useful in the analysis of FMS. Among these are:

1. Inputs and outputs should be in common manufacturing vocabulary.

2. The DSS should be easy to learn and use.

3. The program should be efficient (short running time)

4. The DSS should have what-if capability.

These criteria should be used to the extent possible in the building of any DSS.

The type of studies concerning FMS can be characterized in terms of the level of analysis, and in terms of the stage in the life of the system. For each case defined along these dimensions, several mathematical based techniques can be used.

There are at least three levels at which an analysis of FMS can be done: the machine level, the cell level and the factory level (Gershwin, et al, 1986). At the machine level, problems such as robot arm trajectories, and optimization of performance of each machine are typically tackled. At the cell level, problems are the allocation of operations and tools to machines (considering workload requirements, machine failure, work in process, and processing redundancy) and sequencing of operations. Problems at the factory level are close to organizational issues such as forecasting, material requirements planning, capacity requirement planning, inventory management and overall shop flow control.

The analysis of FMS can also be defined in terms of the particular stage in the system's life. These stages are: design, planning, scheduling and control (Stecke, 1985). To each of these is associated a set of problems. Thus, the design problems include:

- parts specification
- process design
- the determination of flexibilities
- the type of FMS
- the type and capacity of the MHS
- the type, size and buffers (for WIP)
- the computer hierarchy
- the vendors specification
- the layout consistent with the MHS
- the number of pallets
- the number and design of fixtures
- general planning and control objectives
- software development

The planning problems include:

- the part type selection decisions
- the partition of machines into groups
- production ratios

The scheduling problems include:

- the sequencing of input parts
- development of scheduling methods and algorithms
- priorities setting of parts within queues

The control problems include:

- machine breakdown policy
- preventive maintenance policies
- finished goods inspection policies
- tool life monitoring

The typical techniques available for design and evaluation of FMS are: queueing networks, simulation, linear programming, perturbation analysis, network flow analysis and petri nets (Wilhem and Sarin, 1983; Sarin, 1985; Suri, 1985, 1986; Buzacott, 1983). Some of these techniques (such as queueing networks and network flow analysis) are basically analytical, and are appropriate at the early design stage where flow of parts are aggregated. According to Suri, et al, (1986) the advantages of these over more detailed methodologies, such as simulation, are: 1.their robustness and relative insensitiveness to errors of part and equipment data, 2.their ease of use when computerized in a DSS, 3. their ability to absorb relatively rapidly major modifications in the design of the system, (*What-if ability*), 4. their ability to interact with the design process itself which gives them the potential to give a direction of search for improved alternatives, 5. their ability to give good first cut solutions that can be used for eventual simulation runs. Their major limitations, however, reside in their lack of accuracy in certain situations (in the case of blocking, for instance) and for short term decisions.

Graph and network theories have been used in FMS design, planning and control. Directed graphs and networks have the capability of "...specifying production problems relationships for both analysis and simulation" (Passler, et al, 1983). In particular, graphs have been used in the development of petri nets for the precise description of operations and interaction of machines within cells (Merabet, 1986). Networks have been used in describing flows between machines or cells. They have typically led to assignment problems for scheduling purposes (Sarin and Dar-El, 1984)

II-6. SUMMARY

Research on the evaluation of new manufacturing technologies indicates the following problems. First, investments are assessed in terms of financial aspects rather than in a interdisciplinary fashion and also there is a *gap* between operational and strategic implications in the evaluation of new manufacturing technologies. The measure of flexibility of FMS as a whole has been attempted, but not for material handling systems such as AVGS, conveyors or robots (which are typically found here). The value of flexibility has been measured in one study but, again , does not deal with MHS explicitly. Finally, no integrated justification process has been developed that would incorporate the assessment of value of flexibility.

However, a fair amount of research has been done on measures of flexibility either for economic purposes or implementing a design process of FMS. Some of these indices are in fact outcomes or consequences of flexibility (set up time, WIP). Others are related to the combinatorial aspects resulting from the flexibility itself of FMS (number of routings for a given layout).

To recapitulate what has been said in this chapter: The evaluation problem of new manufacturing technologies remains largely unstructured and confusing. A great deal of research has been done on flexibility measures, but an overall interdisciplinary evaluation process and a procedure that would integrate opportunity costs remains to be designed. There are multi-attribute models (the AHP and DIM) that can be used for complex problems such as the one tackled by this research. Any decision framework (conducive to the implementation of a DSS) that attempts to grasp the evaluation problem should be flexible, yet thorough, and not lock the decision maker into one rigid process. Finally, the analysis of an FMS is itself a complex task and such an analysis should be done at the system level. For example, the AGVS itself in order to understand the relationships among design variables and eventually build flexibility measures pertaining to these systems.

This research is an improvement over existing MHS evaluation procedures as it integrates interdisciplinary aspects of systems such as AGVS, and particular variables such as opportunity costs and economies of scope. Moreover, the decision frameworks developed in this dissertation have been designed so that they could be implemented in a DSS that is, to the extent possible, process independent. Finally, the use of flexibility indices is also integrated in these frameworks.

III- RESEARCH APPROACH

This chapter reviews the main objectives of this dissertation and describes the methodology involved. Of particular importance are flexibility indices which are integrated in the evaluation frameworks.

The main objective of this research was the development of one or more evaluation or decision frameworks for new manufacturing technologies, in particular for FMS/AGVS. Another objective was the development and use of flexibility indices within these frameworks. The indices attempt to apply concepts developed in Chapter V about flexibility. These indices are used for more than one purpose in the evaluation process, and it was a goal of this research to illustrate how they are used. In particular, they were used in clarifying emerging characteristics of new manufacturing technologies. These properties will be dealt with in Chapter VI. These indices were used also as performance measures within a multi-attribute model where closeness metrics are used. This is described in Chapter VII. Finally, these same flexibility measures were used in evaluating systems from a purely technical viewpoint. Some typical FMS are analyzed using this viewpoint in Chapter VIII.

III-1 THE EVALUATION FRAMEWORKS

Decision processes, especially multi-attribute decisions, involve at least four problems that must be solved: 1. The alternative generation problem, 2. The modeling problem, 3. The measurement problem, and 4. The ranking problem. The first problem deals with the *direction* towards which the design process must proceed in order to improve current solutions so that the new alternative gets closer to an ideal. For this problem, the displaced ideal model (DIM) is used because of its iterative nature. The second problem deals with using valid models for both design feasibility and system optimization from technical and economic viewpoints. Formal modeling techniques such as simulation and network flows are used in analyzing operational aspects of FMS. The AHP is also used, at this stage, as a semi formal model in order to structure variables pertaining to the evaluation process. The measurement problem tackles the determination of the proper performance criteria pertinent to the system under study. Finally, when alternatives have been generated, their analysis completed and their performance measured, the last problem consists at ranking them in a systematic fashion. In the case of one attribute, simple decision rules, such as cost minimization or throughput maximization, can be used. In the multi-attribute case, each criterion must be weighted and these weights must be combined with flexibility measures in order to have an unambiguous ranking of all alternatives. This chapter describes briefly how all these problems have been solved for FMS/AGVS.

Two main evaluation frameworks have been developed. One for the presence of trade-offs between flexibilities from a technical point of view, and another for the case when these trade-offs do not exist (or are not significant for the current situation). The first framework concentrated on the interdisciplinary nature of the evaluation process, since the flexibilities involved must be weighted in order to have an overall ranking of MHS alternatives. The second framework concentrated on costs since the main problem here was to balance opportunity costs with other costs. Some aspects of one of these frameworks could be used in the other one, but for the sake of clarity, no formal combination of these frameworks has been done in this research. These frameworks are described in Chapter VII.

III-1.1 THE AHP-DIM FRAMEWORK

The framework involving the analysis of trade-offs between flexibilities was developed with the AHP and the DIM. These tools were necessary both from an FMS design and evaluation point of view.

This particular framework involves strategic, economic and technical analyses, and is based on the concept that flexibilities can be in a trade-off relationship . That is, a system that is flexible from a volume point of view can be inflexible from a routing point of view. If a system exhibits such trade-offs, then the problem of weighting the flexibilities has to be solved (in addition to their measurement per se). In order to analyze this first problem, it was construed that the relative importance of a type of flexibility depended on how well it was instrumental in reaching the organizational objectives (comparatively to the other flexibilities involved). Chapter VI analyzes the kind of objectives that are likely to be involved in the evaluation of new manufacturing technologies on the one hand, and the structure that links those flexibilities to these objectives, on the other hand. In particular, it was shown (from a strategic viewpoint) why flexibility as a concept should be involved in the strategic analysis of any organization facing turbulent environments (which are the ones that prevail more and more today) . In a nutshell, it can be said that products' short life cycle and numerous markets' shifts justify the role of flexibility as a fundamental strategic variable. The use of the AHP describes how flexibility can be integrated in this particular analysis (Chapter IV). Basically, those hierarchies used flexibilities at the bottom level and strategic focus at the top so that the former can be ranked with respect to the later. At this point, only the weights associated with each of the flexibilities have been determined. The level of each of these flexibilities still had to be determined with respect to an ideal alternative, which represented a system that had maximum capability on all flexibility criteria. In Chapter VII, where this framework is described in detail, the displaced ideal model (DIM) was used in conjunction with the AHP in order to transform those flexibility measures into a closeness scale which essentially reflected the *position* of an alternative with respect to the ideal one. The combination of the AHP and DIM in this framework permitted the researcher to devise a way to rank FMS alternatives from a flexibility point of view when attributes were in a trade-off relationship. This ranking expressed the relative value of FMS alternatives without other costs such as first and operating costs. Further work still needed to be done in order to integrate these costs. At this point, two sub approaches were used to solve this problem. The first one was to use other types of hierarchies that included these costs and avoid the use of the DIM. In this particular case, the hierarchies used have AGVS (or MHS) alternatives at the bottom level, flexibility parameters at intermediate ones and overall strategic focus at the top. Such hierarchies are described in Chapter VII. The second one was to include other costs in a cost space where opportunity costs were to be balanced against first and operating costs. The theoretical concept behind this idea is described in Chapter IV-2. Basically, the overall flexibility index was used in conjunction with the other costs which were converted into a closeness measure in the same way as for the flexibility indices.

Prior to the strategic and the economic analyses, two other analyses had to be performed in this framework, namely, technical and system analyses. The technical analysis is done in the last part of Chapter IV and the system analysis is performed in Chapter V. The technical analysis is essentially a qualitative appreciation of the components which make AGVS and conveyors flexible. The output of this analysis was then used in conjunction with the system analysis to develop the flexibility indices. A whole chapter is devoted to the system analysis of AGVS, as these systems are complex and involve a large number of variables. The main design variables were determined to be the network topology, fleet characteristics, part routing, vehicle dispatching, and control mechanisms. Moreover, the relationships between these variables were also analyzed by studying existing analyses of AGVS from an operational point of view. The output of this analysis was then used to develop those flexibility indices which will be briefly described later in this chapter (and developed in detail in Chapter V).

The above framework was specifically developed for the case when trade-offs between flexibilities were present. However, it was found that these flexibilities could be supporting of one another. For instance, routing flexibility could go hand in hand with volume flexibility in certain cases. For this reason, another framework which concentrated on the modeling and economics of FMS/AGVS was developed.

III-1.2 THE NETWORK-SIMULATION FRAMEWORK

This framework, involving no trade-offs between flexibilities, was developed using networks flows and simulation modeling, so that all costs (including opportunity costs) could be taken into account.

This framework thus concentrated on the modeling aspect of FMS/AGVS and its economics. The combination of two modeling tools was designed so that system optimization and system feasibility would be both present in the mind of the decision maker. Network models optimize (from both technical and economic standpoints) to the extent possible with a given layout configuration, while simulation models make sure that the given solution is feasible and validates the analytical model. The theoretical foundations of this type of framework are developed in Chapter VI and deal with opportunity costs from a more economic point of view (rather than from a strategic point of view in the last framework) and with the concept of economies of scope, which were linked to operational costs. It was concluded that some were likely to go up while others would go down.

Critical simplifying assumptions were made in order to make the evaluation process more manageable. These are described in Chapter VI. With respect to these opportunity costs, the following assumptions were made. First of all, it was assumed there was a fundamental relationship between flexibility and those opportunity costs, and that this relationship could be estimated in some way by the decision maker (experience or econometric studies, etc). This relationship was further qualified to include the three types of flexibilities that concern MHS within FMS, namely, routing, volume and expansion flexibility. Each of these flexibilities were then construed to be themselves functions of the indices previously developed (Chapter V). More specifically, volume flexibility was assumed to depend on certain types of indices, while routing flexibility was assumed to depend on, or be assessed by, another type of index. Expansion flexibility, as it related to long term effects, was associated with indices that were different from the others which appeared more operational, as these flexibilities are more short term oriented. Another major assumption was that for each of these flexibilities involved in the evaluation of MHS, an opportunity cost could be assessed by the decision maker, and these costs were in a additive relationship so that the overall opportunity cost was the sum of opportunity costs associated with routing, volume and expansion. This type of analysis did not exclude interdependencies (from a technical point of view) between flexibilities, that is, the possibility that the increase in one flexibility implied the increase in another. That would be the case if some flexibility indices were common for both of them or were related to each other in some way. Such interdependencies are explored in Chapter VIII when simulation is used for FMS/AGVS analysis.

The next fundamental theoretical aspect was explored and linked with operational costs (These costs are identified in detail for AGVS in Chapter VII-1). This new concept, economies of scope, describes how costs behave with increasing flexibility of the system. A simple microeconomic model, proposed in the literature, was used as another theoretical underpinning for the justification of mathematical models used in this framework and described in Chapter VII. It was hoped that the use of these models would capture indirectly those economies of scope or at least some of them within a certain range of FMS throughput. This microeconomic model describes how costs behave as product variety increases.

In Chapter VII, the network-simulation framework with its variations is described in detail. Four variations were developed so that refinements could be done by adding an aspect of the decision process each time a new framework was designed. All frameworks involve four types of costs: first costs, costs of current changes, operational costs that increase, operational costs that decrease, and opportunity costs. These costs are identified in detail in Chapter VII-1.

A basic framework was designed to portray a very simple version of the evaluation process involving only one type of flexibility and involving *simple* changes. This framework played the role of describing the basic ideas behind this particular evaluation process, namely, that a change imposed on a system can be either a replacement or an addition to the current system, and that several types of costs must be included in the analysis. Another important aspect of the process illustrated in this basic framework is its iterative nature, which does not lock the decision maker into the same procedure continuously but leaves him sufficient room to explore the problem at hand using different search directions (at both technical and economic levels). Finally, another important feature highlighted here is the operational analysis which combines the use of existing current network models (in this case pertaining to AGVS) and simulation. This particular aspect is described in sections 3 and 4 of Chapter VII.

A first variation of the basic framework was designed to include another type of change which involves overlap phenomena in addition to lead time reduction. These aspects are discussed from a theoretical point of view (Chapter V) and practical examples of these are explored (Chapter VIII).

A second variation of the basic framework included routing flexibility in addition to volume flexibility. Finally, all three flexibilities were included in the last variation of the basic framework which represents the most complete evaluation procedure of its type.

Once these frameworks were outlined, then the operational analysis was developed in detail (Sections 3 and 4 of Chapter VII). The impact of changes within FMS/AGVS was first assessed. It was recognized that a change may affect flexibility (addition), or it could leave flexibility unchanged (replacement). Both cases were considered important and thus treated as separate cases. To each of these cases specific trade-offs were identified, so that the decision maker would be able to assess the effect of the option he has selected. It should be pointed out that the evaluation process can be done on a technical basis only, or the decision maker can go further and add cost parameters in order to analyze trade-offs at the economic level. A technical analysis may be appropriate if the decision maker does not have the opportunity cost functions available. Therefore, the decision framework was designed so that technical and economic analyses could be performed separately. In particular, the operational analysis sub-framework was designed in two stages. A first stage concerned the maximization stage (the technical problem) and the second stage concerned the cost minimization stage (the economic problem). Both of these stages involved the combined used of analytical models and simulation. The sub-framework was designed so that there would be an interaction of these two types of tools. This type of interaction is likely to require several passes before the decision maker is satisfied with the solution. The output of the analytical model would be used as input for simulation. However, in this research, the precise interface between the analytical model and simulation has not been developed and remains a basis for further research.

The sub-framework was designed to recognize the fact that there can be cases when only simulation can be used because of the inadequacy of the analytical models. Therefore, the decision maker has the choice between using simulation or both simulation and analytical models. This concept is discussed in more detail in Chapter VII. The tools involved are network models and *combined* simulation (that is, simulation that integrates both discrete event processes with continuous variables within differential equations).

The discrete part of the simulation describes the chain of events pertaining to parts being processed within the FMS while the continuous part of the simulation models AGVS movements when they are in a loaded, unloaded, idle, blocked, etc, state.

Both simulation and network models were included at the flow maximization stage and cost minimization stage. In this research, simulation was used for the flow maximization stage only (Chapter VIII), while network models are suggested for both flow maximization and cost minimization stages. Models suggested in this research were developed by Leung and Tanchoco (1987), and slightly modified for the purpose of this research. Another model (by Leung, 1987) was also adopted but its implementation was more difficult, as its inferfacing with the simulation model appeared to be more difficult. It is nevertheless suggested as the basis for further research. The Leung and Tanchoco model was chosen because it included parameters on machines and the material handling system (an AGVS with fleet size of one). Thus, this model has the potential to grasp the effect of economies of scope, since it can measure the effect of replacement of machines by other machines that are more flexible. It has also the potential to assess the contribution of the AGVS to these economies of scope. Further research would be needed however to understand the link between this model and economies of scope. At this point in this dissertation it can only be said that this model seems to be appropriate as it includes cost parameters pertaining to machines.

The simulation program involved in this research was chosen so that it could model dynamic aspects of FMS/AGVS that can not be tackled with analytical techniques, or even with conventional discrete event simulation program. A combined simulation/modeling software was used in order to reach this objective. This commercial package (which main features are described in Chapter

VIII) has the ability to basically track both the flow of parts when loaded on vehicles, and vehicle traffic itself. Therefore, dynamic aspects were analyzed for some cases and integrated with the flexibility indices (Chapter VIII).

The research component regarding simulation illustrated that its main limitation is its cumbersomeness for optimization purpose, because of the number of variables that are typically involved. As was said earlier, the limitation of analytical models is their inability to grasp dynamic aspects of FMS such as vehicle congestion and shop locking. Since the decision maker must be aware of these limitations, some of these , in relationship to the Leung and Tanchoco model, were discussed in Chapter VII-6.

An extension of the framework was then outlined as a recursive technique which can be used for a multi-period investment analysis framework. This extended framework was outlined so that a minimization procedure of all costs over a planning horizon could be done. This framework was also designed for determining the optimal investment plan of the introduction of new manufacturing technologies.

Finally, the last part of the dissertation is devoted to the use of the simulation software in the technical analysis of FMS (Chapter VIII). The flexibility indices developed in Chapter V were applied to simple cases involving relatively small FMS. This part of the research is essentially of an exploratory nature and does not present definitive results about the flexibility measures and is to be considered as the basis for further testing on more complex FMS/AGVS and FMS with conveyors.

A baseline model was first developed. It included six machines linked by an AGVS fleet. Three layouts that are typically found in

FMS/AGVS were tested namely, a single loop layout, a double loop layout and a ladder layout with one machine on each rung. These particular layouts were tested, since they are the ones that are typically found in the literature and because of their simplicity. Another reason for chosing these layouts is to test the claim that ladder layouts are better for a large range of products while the single loop layout is better for high flows and low product variety. This hypothesis was partially verified. All segments were unidirectional, so as to simplify the control problem. Tests were made to measure the increase in throughput for varying fleet size and vehicle speed. Some segments were then converted to be bi-directional to assess system performance from a routing point of view. An in-line layout was also tested, but its performance was well below the other ones, as control for segments contention (that is the problem of assigning priority to vehicles simultaneously requesting the same segment) is critical and was thus dropped.

The unidirectional layouts were tested for different fleet sizes and three routings. Relationships between throughput and fleet were then examined. It appeared that the optimal fleet size, that is, the fleet size for which throughput is maximized, was the same for each of the three layouts given a particular routing. Fleet sizes below that value could not fully use the FMS's capability, but fleet sizes above the optimal fleet size created excessive blocking and therefore a decrease in system throughput. The single loop layout appeared relatively resilient to throughput degradation for routing changes that increased the load on the AGVS. Therefore, for routing flexibility (according to this definition), the single loop layout was considered more flexible than the other ones. The same analysis was then performed on the same layouts with some bidirectional segments. The results showed that, in this particular case, the ladder layout was superior in both volume and routing flexibility, as the other layouts experienced severe blocking problems.

Flexibility indices pertaining to volume flexibility were then computed. In particular, the ratio of the percentage change in throughput to the percentage change in fleet size was computed for the unidirectional case. Unfortunately, the elasticity indices for volume flexibility did not discriminate very well between layouts as their performance was not far from each other. Flexibility indices based on the efficiency and effectiveness concepts (discussed in Chapter V) were also computed for the same cases and relationships were sought between efficiency and the effectiveness of the system for a given routing. However, those relationships were obvious as the alternative layouts were exhibiting similar performance. Thus, the improvement in terms of throughput could be appreciated as fleet size was increased.

Variations in speed were then tested for one layout and for one routing. As expected, the higher the speed of vehicles the more flexible the AGVS were (from a volume flexibility viewpoint) and the lower the optimal fleet size.

The FMS was modified to include interstation buffers. This was done for improving both volume and routing flexibilities. The same conditions in terms of product mix prevailed except that demand was increased as the system then was able to process twice as many parts as for the base model. It could be seen that this type of FMS/AGVS was far superior to the FMS without buffers as throughput increased and the number of possible routings increased as well. It was therefore concluded that this type of system was significantly more flexible than the system without buffers.

Comparisons were also made between two layouts (with buffers): the single loop layout and the ladder layout. The phenomenon of blocking was significant for one routing, as the single loop layout was slightly inferior in terms of throughput to the ladder layout, which experienced less blocking. Moreover, the single loop layout was also dominated on almost all fleet sizes for routings that significantly increased the load on the AGVS.

III-2 THE FLEXIBILITY INDICES

The flexibility indices developed attempted to reflect the concepts discussed in Chapter V. These concepts were developed from the analyses of Chapters IV and V.

This research also illustrates the multiple role of the flexibility indices that were used in the development of both frameworks. These indices not only play a role in the measuring problem, but also in theoretical aspects of flexibility as they shed light on what type of opportunity costs that must be taken into account by the organization when considering investment in new manufacturing technologies.

The flexibility indices were devised in a way to reflect specific aspects of flexibility itself. Most of these measures are related to throughput which is itself a typical performance measure for AGVS (and up to a certain point, conveyors). Others indices reflected other types of flexibilities, in particular routing and expansion which are typically associated with MHS within FMS. These indices were not necessarily associated with system throughput, but with other aspects such as product mix and cost of change which are themselves aspects linked with opportunity costs.

Two types of flexibilities were developed in this research. The first type was called an elasticity type of flexibility and the second, efficiency and effectiveness type of flexibility. They were mostly related to volume flexibility as they are involved with system throughput. Other parameters were related to routing flexibility, since the above concept of flexibility could only be partially applied. Furthermore, simplifying assumptions had to be made with respect to product variety as it is related to machine scheduling and vehicle routing in order to have a better idea of how to measure this type of flexibility. Volume and routing flexibility were then applied to real cases (Chapter VIII). Indices pertaining to expansion flexibility were also suggested (Chapter IV), but they were not applied to real cases in this research.

Elasticity indices of flexibility were developed based on the system analysis of AGVS (Chapter V). Recall that this part of the research was devoted to the analysis of AGVS from an operational viewpoint. The main conclusion of this analysis was that the important parameters in the design of AGVS were system throughput, lead time, vehicle fleet size, system load and system capacity. This conclusion guided the development of the indices, at least for volume flexibility. The concept of elasticity was applied to flexibility in order to link a manufacturing system to its environment. More precisely, to link the possible response of a system facing an environmental perturbation. The ratio of the perturbation to the response was then construed to be a measure of flexibility. If a system was able to respond with little internal changes to an environmental perturbation, it was considered more flexible than another one which would require more resources in order to respond to that same perturbation.

A list of typical environmental disturbances was then established, along with several possible responses for AGVS. This list was based on the preceding system analysis. Disturbances were identified as changes in demand, product mix, and machine breakdown. These perturbations were considered typical of what makes an environment turbulent (Chapter IV), and were based on the analysis of economic conditions which are more and more prevailing. Typical responses to these perturbations were suggested (in the case of AGVS) and were based on the technical and system analyses. These were identified as: responses associated with fleet characteristics, (vehicle speed, vehicle capacity, buffer distance), changes in routing, changes in vehicle dispatching rules, changes in the layout (spurs and cutbacks), changes in segment capacity, and changes in segment directionality. Some indices could be constructed easily for volume flexibility. Thus flexibility indices were suggested as the percentage change in throughput (demand) for percentage change in fleet size; percentage change in throughput (demand) for a percentage change in vehicle speed.

The second type of flexibility index was also construed to be related to volume flexibility as it involved system throughput, but its aims are slightly different as it is related to MHS efficiency and effectiveness. The efficiency concept of flexibility was defined as a closeness index to a perfect MHS while the effectiveness concept measured the closeness of throughput to system capacity and are described in detail in Chapter V. (These concepts are not to be confused with the concept of the ideal alternative discussed in the description of the DIM) There were two main reasons why this type of index was developed. First, it shows how throughput can increase as lead time decreases and overlap increases. A second reason was that it can be used to look at the trade off between the cost of sojourn time of a part versus costs of having a more efficient MHS.

This second type of flexibility index was used to show how fast an MHS can get close to the perfect MHS (Chapter VIII). In this sense, a MHS was thought to be flexible if it could exploit the machine's capacity and capability with minimum resources.

Routing flexibility was more complex to deal with, and an important assumption about product variety had to be made in order in simplify its analysis. More specifically, it was assumed that each product had only one operation set and one possible machine sequence, so that, within this very narrow view, routing flexibility was directly related to product variety. In other words, a system was considered more flexible from a routing point of view if it could produce a larger product range, each product having its own machine routing. However, other indices were also adopted for this particular flexibility in order to have a more complete picture. The use of the elasticity indices were used in measuring the degradation of system performance when product mix was modified and which resulted in increasing system load. Finally, a measure of vehicle blocking was also used and associated with a layout and a AGVS fleet size.

III-3 SUMMARY

The major contributions of this research are the development of an overall structure of an evaluation process (which can be implemented) for new manufacturing technologies and the development of operational measures of flexibility. The thoroughness of this evaluation process permits an interdisciplinary study of FMS/AGVS, but is general enough to be extended to other types of MHS such as conveyors and to the design of FMS.

More specifically, this research shows how the AHP and DIM can be combined together in order to generate an interdisciplinary evaluation process. It also shows how analytical techniques can be combined with simulation in order to measure the performance of AGVS, both from a technical and economic standpoint.

IV- STRATEGIC, ECONOMIC AND TECHNICAL ANALYSES

This chapter deals with strategic, economic and technical issues of material handing and, in particular, AGVS. The technical part attempts to capture the variables that affect flexibilities and explain more specifically how each type of flexibility can be achieved by alternative characteristics of MHS. The strategic analysis gives a framework to assess the weights of each of the flexibilities in the face of strategic issues. The economic analysis looks at the trade off concept between first costs and opportunity costs associated with these systems.

IV-1 STRATEGIC ANALYSIS

In this first section, the rationale behind investing in flexibility from a purely strategic point of view is described. In the first part, questions such as "Why do firms need to be flexible ?" and "What do firms need to be flexible to ?" are explored. In the second part, a hierarchy that links the three types of flexibilities with Porter's (1980) generic strategies is developed. This last analysis gives a framework for determining the (a priori) weights of those flexibilities in the face of overall strategic goals.

What follows is some philosophical considerations on the role of technology within organizations in the face of new environmental trends. The fundamental idea is that FMS are more in tune with turbulent environments than classical productions systems. It is assumed here that AGVS or conveyors can also contribute significantly to reaching overall goals, since they are part of what makes a manufacturing system flexible.

IV-1.1 FLEXIBILITY AND OVERALL STRATEGY

Flexibility is not a new concept in manufacturing. However, this aspect of production technology has become a strategic issue, since the economic environment (opportunities, threats and responses from competitors, timing of competitive moves, and societal concerns) that organizations face today has become more turbulent, and because it is related to capital intensive investments which have strategic implications. Flexibility is related to organizational effectiveness, efficiency, and innovation as product variability has expanded for a given market on the one hand and as technology must reflect the firm's environment on the other hand.

Planning for new technologies inevitably raises the fundamental issues of which particular technology to implement (Moore, 1987; Mize, 1987), the scheduling of its implementation (Mize, 1987) and the compatibility of the manufacturing strategy with overall business objectives (Mize, 1987; Hayes and Wheelwright, 1984).

The last issue of strategic planning for manufacturing technology is concerned with the compatibility of the manufacturing strategy itself and the overall business strategy. This fit is particularly critical as the dimensions of the manufacturing strategy are pervasive throughout the firm (Hayes, and Wheelwright, 1984). The manufacturing strategy must therefore be consistent (Porter, 1980), so that manufacturing goals are not only supporting organizational goals but are mutually compatible within themselves. This insures that the manufacturing strategy is consistent with the environment. It also insures that resources owned or to be acquired are truly instrumental to accomplishing manufacturing goals and policies.

To understand the issues that tie together manufacturing flexibility and strategic considerations, the fundamental purpose of technology within the overall organization has to be examined in the light of new technologies such as FMS and CIMS. Traditionally, technology has been considered as the set of instrumental means necessary to achieve organizational goals. Thompson (1967) refers to technical rationality playing the role of a closed system of logic shielded from external influences as it tends to instrumental perfection. Based on the hypothesis that in order to "...maximize productivity of a manufacturing technology, the technical core must be able to operate as if the market will absorb the single kind of product at a continuous rate, and as if inputs flowed continuously at a steady rate and with specified quality", the organization will seek to protect that technical core by isolating it, buffering it, leveling its relationships with the environment, etc. In this sense, norms of rationality say that the technical core is fundamentally at odds with the exterior system as it demands certainty, a characteristic that the environment usually does not have. The classical answer to this paradox or conflict has been for organizations to add input and output components to their technical core so that it could function as if it was facing, to the extent possible, a certain and predictable environment (developing thus what Thompson called "organization rationality").

FMS and CIMS are specially designed to deal with a complex and unpredictable environment. The major characteristic of these technologies is to be able to deal simultaneously with a variety of demands and respond to them in a very short time, in a way that is clearly as efficient as the one product continuous flow manufacturing system on which rationality norms are based. In a way, a FMS is a system not to be isolated from its environment, but rather is a system to be closely linked with it. In other words, an FMS, because of its high technological sophistication is able to "internalize" the uncertainty coming from the environment and thus respond to it efficiently.

As a consequence, strategic evaluation of new technologies should take into account the concept of flexibility (and its operational measures), as new norms of rationality seems to take over the old ones. Such norms would call for maximizing flexibility, internalizing uncertainty, maximizing linkages between the technical core with its environment... This is not to say that organization rationality (input activities, technological activities, output activities) is breaking down. However, its role is changing. Instead of seeking to isolate the technical core from its environment, its function will be to develop "on line " relationships working on a "real time basis", so that the manufacturing system interacts as it should, given these novel capabilities. In section II-3.2 it was noted that Kumar and Kumar (1987) developed what they call entropic measures of flexibility reflecting the fact that the system, must be as complex as the environment it is dealing with. In this sense, to a high entropic environment must correspond a high "entropic" technological core (exhibiting high flexibility in action). This "internalized entropy" is a way to deal, from a managerial point of view, with a highly entropic environment (that is, an environment from which little is known). To put this in another way, technology and structure must reflect the environment (Thompson, 1967). If the organizational system is facing a highly complex environment, it must confront it with a technology just as complex.

As noted in the first section, the concept of flexibility is likely to link managerial planning that deals with overall strategies such as cost leadership, product differentiation and market focus (Porter, 1980) with the engineering type of planning which is concerned with part selection, partition of machines...(Stecke, 1985). Flexibility concepts would then link operations to strategic goals of the firm. Manufacturing technology is a tool to reach an objective and, as such, remains subordinate to organizational goals, but it has been promoted from tactical to strategic importance within the planning process.

In light of the preceding discussion, it can be said that flexible manufacturing systems and CIMS are likely to alter the determinants of the intensity of competition in a given market. A firm investing in such integrated systems may have, on the one hand, an effect on the availability of market substitutes and on the power of buyers (output flexibility) , and, on the other, an effect on entry barriers and power of suppliers (input flexibility). A shift in competitive rivalry is also likely as FMS and CIMS give to the firm a better way to counteract threatening moves by competitors by reducing retaliation lags (process flexibility), and as it devises defensive or offensive actions either by better positioning itself in the face of the prevailing competitive forces or by influencing these forces (with overall system flexibility).

Because the core technology is better in tune with its environment, strategies exploiting changes in the product (or factor) market can become more effective (especially for diversification or market entry purposes). A particular environment where it seems appropriate to use flexible manufacturing systems and other technologies is in fragmented industries. Fragmented industries are industrial settings where each firm has no significant share of the market, yet each of them has the power to influence industry outcomes (Porter, 1980). Such environments are characterized by factors such as diverse product line, diverse market needs, high product differentiation. Accordingly, firms cope with fragmentation with classical responses like decentralized structures, specialization by product type, customer type, order type, or geographical area. These firms do not have a high market share because of the presence of diseconomies of scale typical of such environments. FMS and CIMS technologies could add to the set of possible competitive moves by creating economies of "scope", that is, "...potential for low-cost production of high-variety , low volume goods" (Kaplan, 1986). Such strategy would be a solution to the diseconomies of scale problem. Instead of trying to overcome fragmentation (by precisely breaking those diseconomies of scale), it would be dealt with directly with increased flexibility.

IV-1.2 FLEXIBILITY HIERARCHIES

The problem, at this point, is to give a framework that can determine the importance of each of the flexibilities of material handling systems in the face of overall strategic goals. The AHP can be applied to strategic planning by confronting the likely scenarios with the desirable ones, given a set of policies or actions (Saaty, Kearns 1985). This process involves the use of several hierarchies iteratively, so that convergence is obtained between likely and desirable outcomes or scenarios. However, a simpler approach using a single workable hierarchy can also be implemented to make explicit the link between MHS flexibilities and overall strategic goals. Figure 8 illustrates such a hierarchy. At the bottom level are the flexibilities and at the top level is the overall focus or goal. The second level is the time scope to balance short and long term considerations (Sullivan, 1986; Hämäläinen , 1986). The third level represents typical generic strategies that a firm can pursue individually or simultaneously (Porter, 1980):

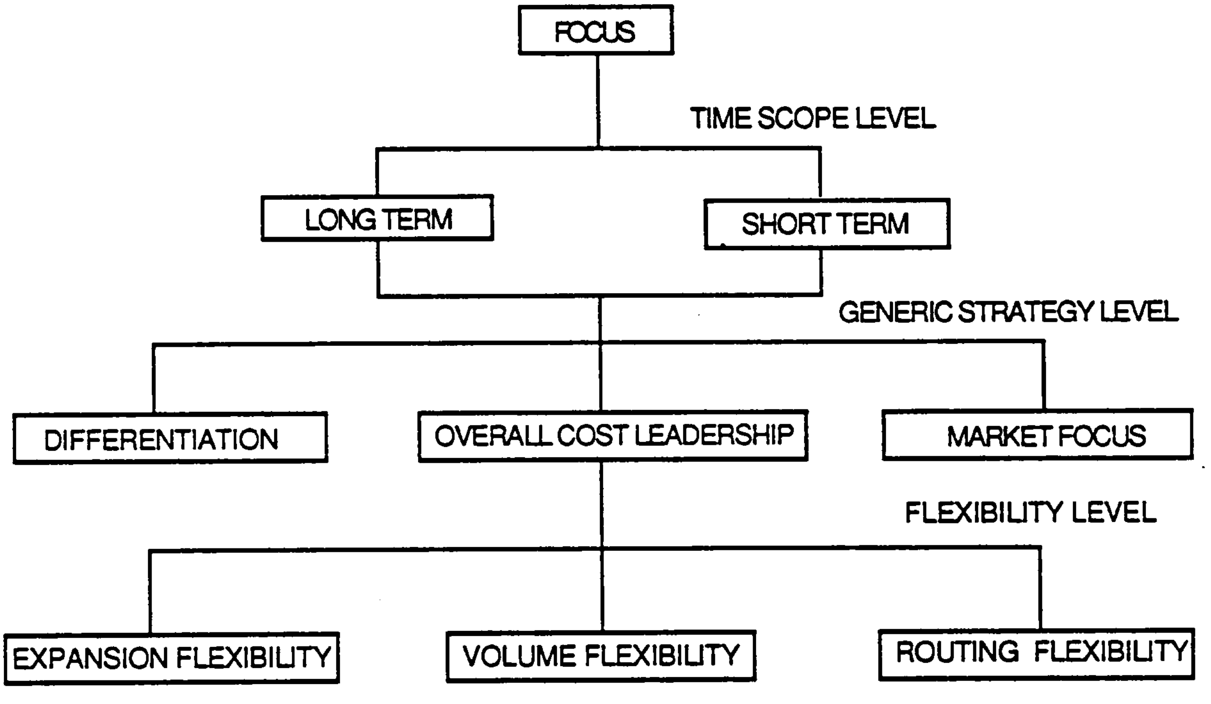


FIGURE 8. HIERARCHY FOR STRATEGIC ANALYSIS INCLUDING PORTER'S GENERIC STRATEGIES

overall cost leadership, product differentiation and market focus. Overall cost leadership is essentially establishing low cost position with respect to operating costs (variable and overhead). The concept of opportunity cost will be treated in the next section. Product differentiation is a strategy for competing on the basis of product characteristics in terms of quality or other variables such as response time. Market focus is essentially a strategy that concentrates on one or several markets.

A second hierarchy (Figure 9) illustrates similar relationships between flexibilities and strategies. The strategies involved, however, are more explicit and better describe operational issues facing FMS. For example, if it is clear that lead time and product range are paramount in the survival of the firm, then the second hierarchy should be used.

The main difference between hierarchies is that the first one is less specific than the second one. The first one is market oriented and concentrates more on what the firm produces and for whom it produces. The second one looks at the production aspects of the system manufacturing the product.

IV-2 ECONOMIC ANALYSIS

In this section, economic analysis of MHS essentially refers to the value of flexibility. This particular aspect of the evaluation of manufacturing systems was reviewed in section II-4.2 The main question here is if it makes sense from an economic point of view to invest in capital intensive equipment that will most likely increase fixed costs or overhead. The answer seems to lie in the proper assessment of those intangible costs associated with

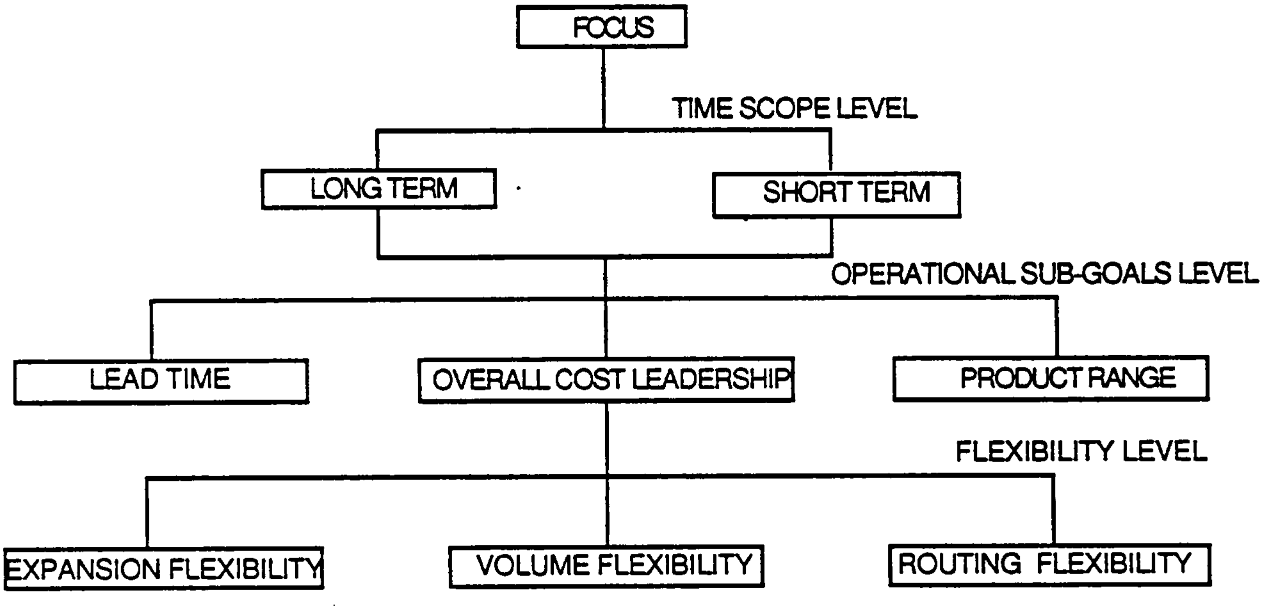


FIGURE 9. HIERARCHY FOR STRATEGIC ANALYSIS INCLUDING OPERATIONAL SUB-GOALS

lost sales and system response. In other words, it seems inevitable that investment justification in MHS for FMS cannot be based on traditional costs alone, but also on these opportunity costs which can only be forecasted and estimated approximately.

Flexibility can be associated with the opportunity costs incurred when investing in a particular manufacturing system. The more flexible a system is, the lower the opportunity costs when internal and external disturbances occur. These costs can be expressed in terms of lost sales due to poor lead/response time, or narrow product range. Another proxy for opportunity costs is changeover costs resulting from investing in a less sophisticated system, which is cheaper, yet does not deliver sufficient flexibilities. In any case, it would seem to make sense that the higher the investment in FMS (and MHS), the more flexible is the system and the lower are opportunity costs. As suggested in section II.4-1 , a balance between first costs and opportunity costs tends to minimize overall costs (see Figure 10).

Therefore, the first cost of these systems is expected to be relatively high. Some operating costs may increase while others decrease. The benefits from the operational standpoint can be substantial according to Miller (1987). Potential savings and cost increases generated by AGVS are the following:

Savings:

- Manpower savings
- Space savings
- Maintenance savings
- Reduced material handling damage
- Reduced peripheral MHS
- Increased throughput
- Reduced workforce injuries

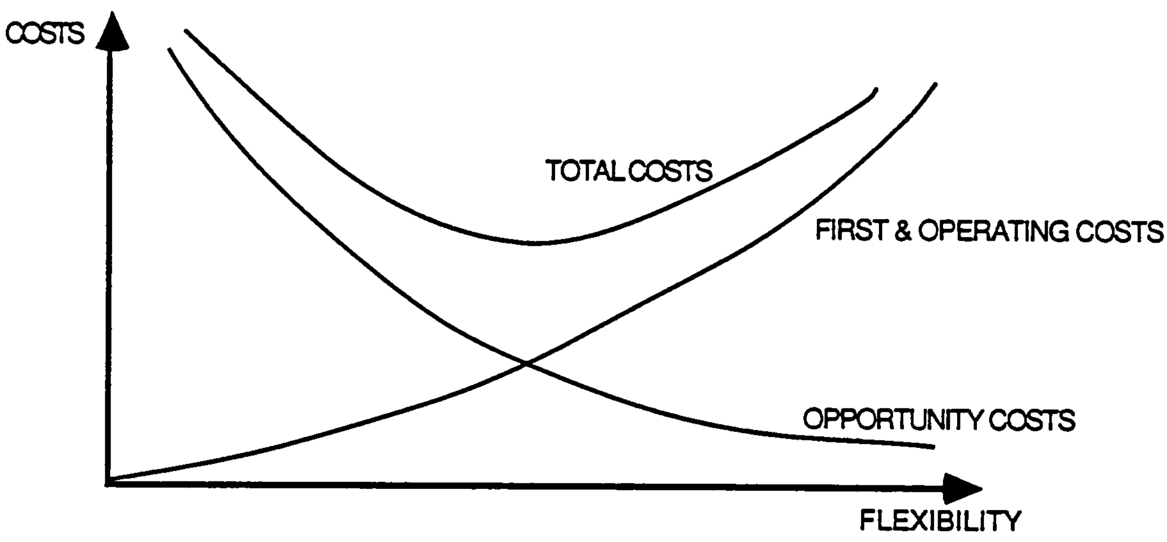


FIGURE 10. OPPORTUNITY COSTS AND FLEXIBILITY

Costs:

- Costs due to break in period
- Costs due to maintenance training
- Costs due to system and training support.

IV-3. TECHNICAL RELATIONSHIPS BETWEEN FLEXIBILITIES

Figures 11,12 and 13 illustrate the relationships between flexibilities and technical variables pertaining to AGVS. In Figure 11, the set of variables to which each of the flexibilities are likely to depend on are displayed in separate hierarchies. All these are synthesized in a single hierarchy in Figures 12 and 13 where interdependencies between flexibilities are also displayed.

Based on the prevailing relationships among AGVS design variables , it seems reasonable to believe, for instance, that volume flexibility, the capability to operate for different demand levels, can be accomplished by adding vehicles, increasing their speed, or using vehicles with higher load capacity. Volume flexibility could also be achieved with a layout topology that could be modified slightly, such as adding spurs or cutbacks at the proper places in the network so as to accommodate the increase in flows. Routing flexibility would seem to derive from network characteristics that permit full exploitation of the flexibility of cells. Expansion flexibility is somewhat different from the other two, as it involves major additions in terms of cells. Here , the major considerations would seem to be the control software and its respective programming. However, the network configuration might also play a substantial role. Does adding a cell require more

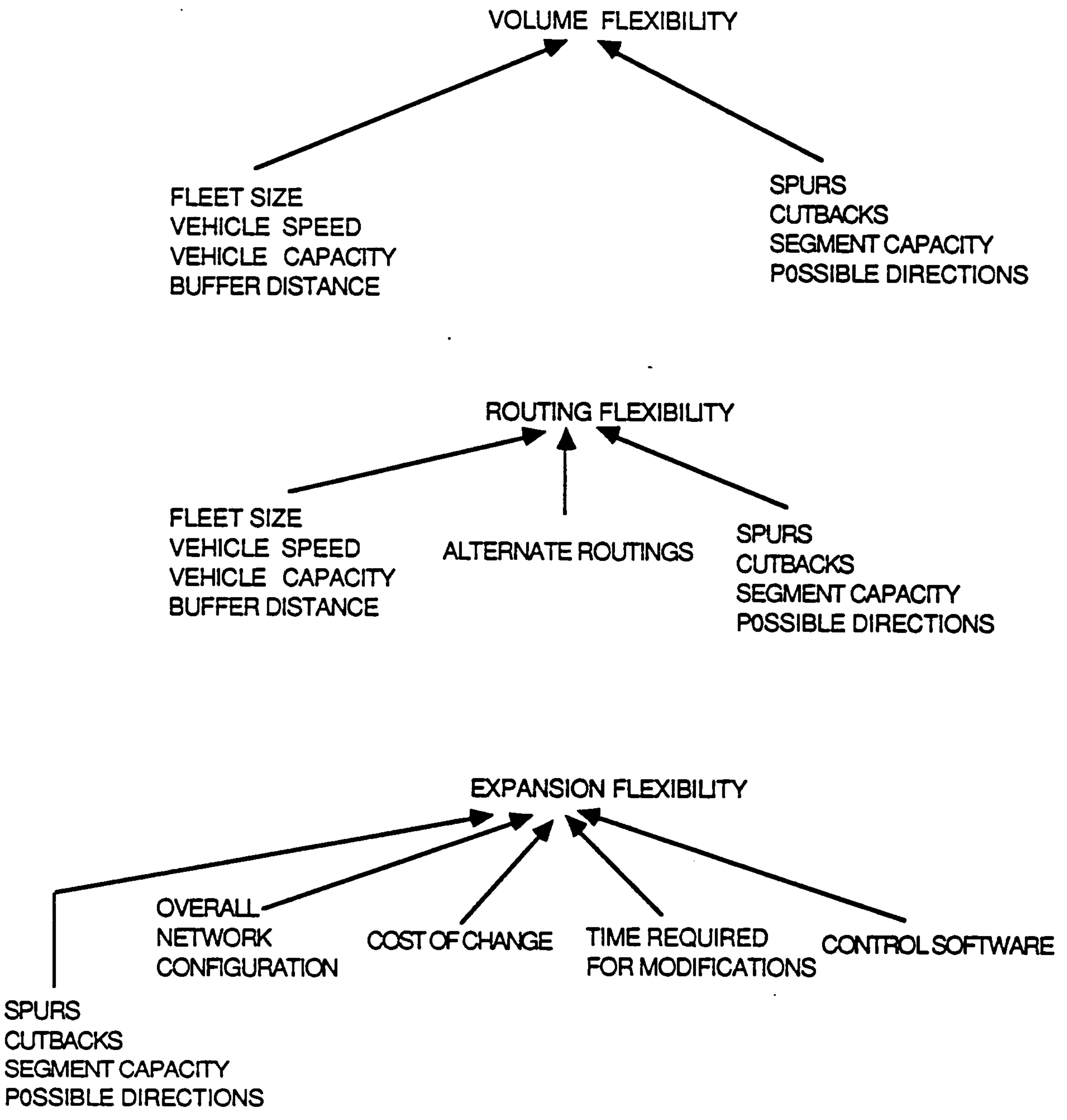


FIGURE 11. VARIABLES AFFECTING FLEXIBILITY
(AGVS)

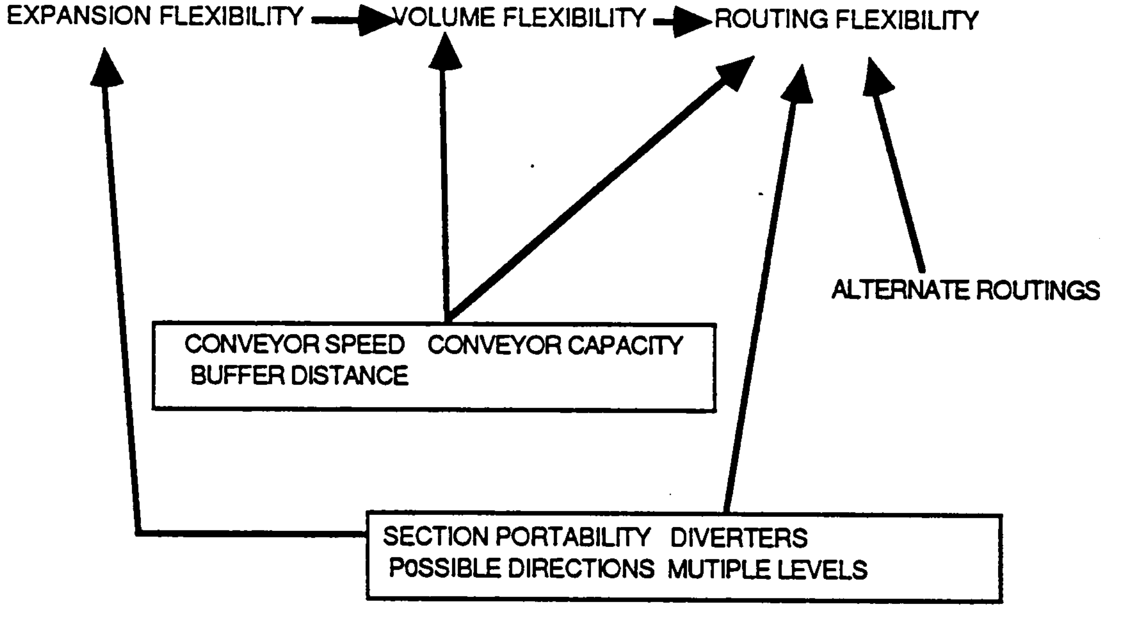


FIGURE 12. INTERDENDENCIES BETWEEN FLEXIBILITIES
(CONVEYORS)

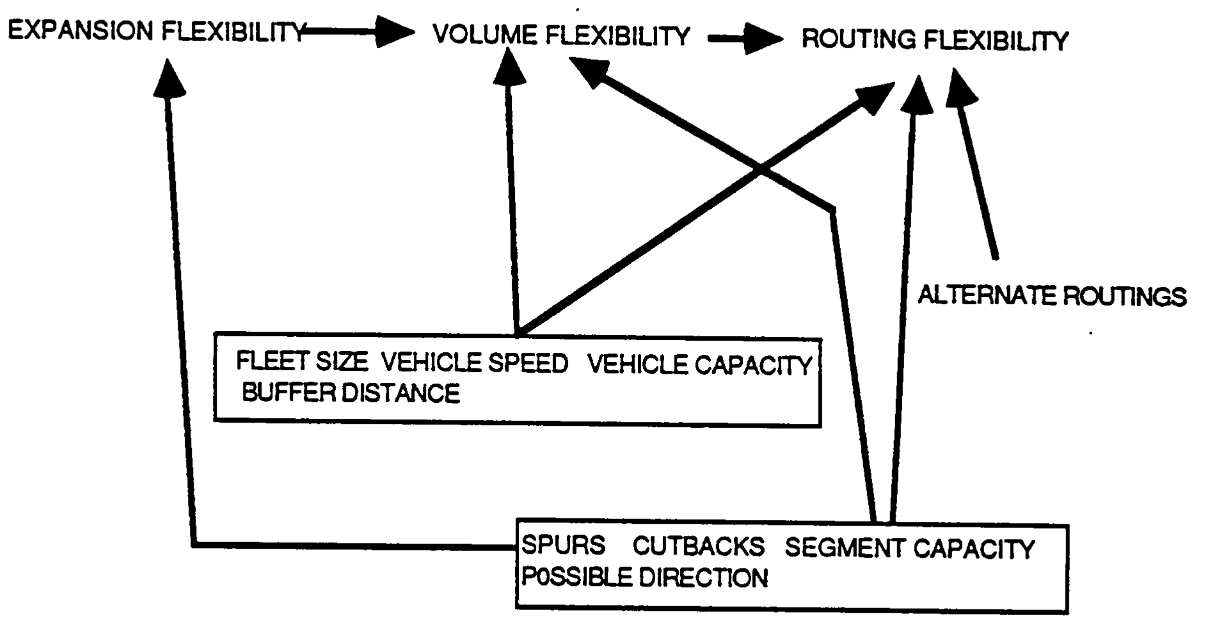


FIGURE 13. INTERDENDENCIES BETWEEN FLEXIBILITIES (AGVS)

spurs and cutbacks for a particular layout than another ? In other words, does it make the system more complicated ?

Finally, as it was mentioned earlier, flexibilities may not be totally independent of each other. Volume flexibility favors routing flexibility, and expansion flexibility does contribute to volume flexibility in the long run.

The analysis was also carried out for conveyors even though AGVS is the main focus of this research. This is to show that interdependencies does not seem to concern AGVS only.

IV-4. SUMMARY

This chapter attempted to give an overall, interdisciplinary view of of the evaluation problem of new manufacturing technologies, in particular AGVS within FMS. At this point, strategic, economic and technical aspects of these systems were explored. The first section explained why flexibility was a strategic issue for firms facing turbulent environment. Hierarchies were developed in order to integrate flexibilities within tools that could be used in strategic analysis. The second section links flexibility with opportunity costs and develops the concept of an optimal level of flexibility which balances the (tangible) costs of acquiring flexibility and the (intangible) opportunity costs. Finally, the last section looked at what is contributed to flexibility from a technical point of view. System components were identified which were thought of as contributing to MHS flexibility especially AGVS. Conveyors were also considered as these system are also encountered in FMS.

This chapter laid the groundwork for an integrated view of flexibility as it is related to MHS. The strategic analysis attempts to justify the importance of flexibility and identify which type of flexibility is more important than the others. The technical analysis tries to understand what makes a system flexible. Finally, the economic analysis looks for the proper amount of flexibility. In the next chapter, AGVS are analyzed from an operational or system point of view, in order to grasp the relationships between some of the more important variables previously listed in the technical analysis. All these analyses, strategic, economic, technical and operational, form the basis upon which the flexibility indices are constructed.

V- FLEXIBILITY OF MATERIAL HANDLING SYSTEMS

In this chapter AGVS are analyzed from a system point of view, so that the most important variables pertaining to flexibility may be isolated. It appears that the main parameters involved in AGVS analyses are throughput, lead time , vehicle fleet size , system load and system capacity. The following analysis guides the development of flexibility indices which capture the role these variables play in the evaluation of AGVS. This chapter highlights another important aspect of AGVS, that is, its dynamic aspects. These are shop locking and vehicle blocking, not always grasped by analytical techniques and for which simulation modeling is needed.

V-1. PARAMETERS INVOLVED IN AGVS ANALYSES

When designing an FMS and assessing its performance, a large number of interrelated variables must be taken into account. These are classified below in five categories.

- Network topology
- Fleet characterization
- Routing
- Dispatching

• Control

The network topology is basically the layout of the manufacturing system where cells are connected with AGV tracks or conveyors. Fleet characterization looks at individual capabilities of the automated guided vehicles themselves, such as load capacity, speed, etc. The routing of parts is concerned with the machine (cell) ordering or sequencing. This aspect determines the direction of material flow from machine to machine. Closely related to routing are the dispatching procedures, when one vehicle among a set of idle vehicles has to be sent to a requesting cell, or when several cells simultaneously request one idle empty vehicle. Finally, the control mechanism, while not a set of variables, remains an essential aspect of an automated FMS, as it makes possible the coordination of parts and vehicles, and integrates the flow of materials within the system.

Because of the complexity of these systems and their high number of variables, models developed are conditioned with several assumptions which restrict their scope (Wilhelm, Evans 1987). In other words, studies of these systems concentrate on a particular type of variable, or on a particular problem (fleet size determination for example) associated with AGVS. However, these analyses can nevertheless give an appreciation of how variables are intertwined.

The following discussion of the categories applies primarily to AGVS. However, some aspects of these systems can also be applied to conveyor systems where layout, routing and control must be examined as well.

V-1.1 Network Topology

Section II-3 mentioned four *basic* layouts typically found in flexible manufacturing systems: loop, ladder, in-line and open field. However, any type of combinations could be done from these. For example, intermediate configurations can be created from combining the loop and ladder layouts. The loop type FMS is typically one closed AGVS track (or a single conveyor as a primary MHS) where machines are located around that track. The ladder configuration is composed of a loop with inner rungs on which each machine is located. It is easy to generate a ladder configuration where more than one machine is placed on each rung, thus resembling somewhat the loop configuration. Moreover, several ladder configurations could be intertwined to form an open field layout.

Establishing the layout of an FMS is usually done heuristically, based on some *standard* configuration which seems to make sense. Line, loop and ladder configurations are the ones that appear periodically when designing FMS with AGVS or conveyors. The loop and ladder systems are presumably useful when loading and unloading stations are positioned at the same place in the layout. They are also convenient for routings requiring parts to cycle several times within the system before they are fully processed.

Some efforts have attempted to take into consideration layout characteristics in the FMS design (Bartholdi, et al, 1987; Sharp, Liu 1987; Tanchoco and Egbelu,1987). The main problem is to characterize unambiguously a particular AGVS track configuration. From a graph theoretic standpoint the number of segments linking a complete n node graph is $n(n-1)/2$. Such a graph would correspond to a layout where there is a direct path from one cell to another. In practice, however, few machines may be linked in this fashion.

Several paths from one machine to another may require passing some other machines on the way. Therefore, the number of such direct links between machines are likely to be less than n(n-1)/2. However, if machines are to be linked by paths that minimize the number of machines to be passed on the way, then branch and merge points between these machines must be added. This has the effect of increasing the number of nodes in the graph. Not only does the number of these nodes have to be estimated in the design process, but their spatial positions with respect to machines must be determined in some way in the overall layout of the FMS. As in the case of the number of vehicles, not enough of them might result in blocking (an AGV waiting behind another one). Too many of them might result in a very complex system where coordination between parts and vehicles (crucial in order to avoid shop locking phenomena) may become complex as well.

Typical layout studies of AGVS restrict themselves to the loop track layout as a baseline for the study of performance of FMS. A network topology classification (Bartholdi, et al, 1987) has been proposed using series-parallel graphs. However, this classification does not seem to include the in-line and ladder type of FMS as was described in section II-3. In one study,(Sharp and Liu, 1987), a minimization of total system costs is attempted via a mixed integer programming network model. The idea is to determine the cutbacks and spurs that will optimize some performance measure. In this case, system costs are composed of network costs, on the one hand, which are themselves functions of the number of shortcuts and cutbacks , and on the other hand, on load carriers costs which depend on the number of vehicles, routing and delays. Another study (Maxwell and Muckstadt, 1987) examines the idea of track balancing within an AGVS/assembly line system as a characteristic associated with vehicle blocking. In this study, three criteria are used to characterize a balanced AGV segment for an assembly system where the vehicles travel in a loop fashion (from a warehouse to delivery points) on unidirectional tracks. The particular layout used is a combination of two ladder configurations positioned back to back. The first criterion says that a track is balanced if the number of vehicles entering the particular segment and stopping at stations somewhere on it for pick up and delivery activities is equal to the minimum number of vehicles required on that segment, assuming it could reverse direction on it (Maxwell and Muckstadt 1987). Such a segment has its stations positioned in such a way that empty vehicle time is minimized. The second criterion is that some segments should only be used for transfer loads and no machines or cells should be positioned on it. For example, tracks linking loading/unloading stations to machines should be transfer aisles only. Finally, on the one hand, the drop-off and pick-up activities on a segment should be equalized to the extent possible , and on the other hand, the number of AGV that unload should be equal to the number of vehicles that load parts on that segment.

In summary, it can be said that the *layout decision* is essentially concerned with:

- spatial disposition of machines/cells.

- the number of branching and merge points between these machines (spurs and cutbacks).

- the length of the segments linking machines to merge and branch points, and between these points.

- the capacity of these segments in terms of how many vehicles can be simultaneously located on a particular segment.

• the number of possible directions on a segment (unidirectional or bidirectional).

Based on the track balancing concept mentioned above, a general characteristic can be noted about networks. Some segments are used for servicing machines (that is, machines are stationed at these segments), whereas some others are only there for transferring loads from one machine to another and are also used as shortcuts to bypass some machines, that might otherwise be in the way of other traveling loads. A loop configuration only has segments that service machines, whereas a ladder configuration also has segments that permit loads to go to any machine without going to a segment where an alternate machine is on the way. The combination of transfer segments and service segments appears to have an influence on the proper overall layout configuration.

V-1.2 Fleet Characterization

Fleet size has been a problem that several researchers have attempted to solve analytically as well as using simulation (Maxwell and Muckstadt, 1987; Egbelu, 1987; Tanchoco, et al, 1987; Wysk et al, 1987 ; Hollingworth, et al, 1987). Fleet size may be determined with time independent analyses (using from-to charts for example). However, the number of vehicles thus determined (which is considered to be the minimum necessary to perform the task) may well be insufficient if blocking, due to layout characteristics or other dynamic phenomena, arises. In this case, the minimum fleet size may be higher as a time dependent analysis (such as simulation) might show.

In summary, the parameters associated with automated guided vehicles are the following:

- fleet size (number of vehicles per fleet).
- load capacity per vehicle.
- vehicle speed when loaded and when empty.
- vehicle acceleration and deceleration.
- vehicle length.
- buffer distance between vehicles (minimal distance allowed).

Other characteristics mentioned in the literature pertaining to the AGV fleet include vehicle availability (or reliability), energy capacity of batteries, navigation techniques, pallet design...(Karlsson, 1987; McEllin, 1987 ; Boegli ,1987; Jansson, 1987).

V-1.3 Routing of Parts

The routing of parts would seem to be, at least at the outset of system design, a problem concerning cells and machine processing capability. However, it becomes a material handling problem when distinct flows of parts are intertwined with each other on the factory floor thereby creating possible blocking phenomena. Moreover, as was discussed in section II-4.2, one part may be processed in alternative ways on machines/cells, resulting in an operation set having more than one feasible sequence, which in turn generates a set of alternative routings. Dynamic routing mechanisms may be advantageous when blocking and machine breakdowns occur so as to utilize the potential flexibility of cells.

Some optimal routing can be done in a math-based programming fashion by neglecting dynamic effects such as blocking (Blair, et al, 1987). Such models are approximations of some sort of time-dependent analyses which add in the effect of congestions. Such disturbances may require secondary optimization of the scheduling process (Ránky, 1986). In other words, if optimal routing cannot be determined at the outset of system design, then secondary optimization becomes advantageous. This can be accomplished with a decentralized control in a distributed net fashion that promotes flexibility.

V-1.4 Dispatching of Vehicles

The effective control of automated guided vehicles requires that procedures be determined (during the design process) when one of the following situations occurs (Egbelu and Tanchoco, 1987; Pritsker, 1986) :

- one among several empty and idle vehicles must be chosen in order to service a requesting machine for load pick up (work-center-initiated dispatching rules).

- one among several requesting machines must be chosen, so that a single idle vehicle can be dispatched (vehicle-initiated dispatching rules).

- a vehicle is empty and no request has been placed for it (idle vehicle rules).

- two vehicles request the same segment simultaneously (contention rules).

Among the possible rules available for these situations are:

- Work center initiated dispatching rules:
    - Random vehicle rule
    - Nearest vehicle rule
    - Farthest vehicle rule
    - Longest idle vehicle rule
    - Least utilized vehicle rule

- Vehicle-initiated dispatching rules:
    - Random machine rule
    - Shortest travel time/distance rule
    - Longest travel time/distance rule
    - Maximum outgoing queue size rule
    - Minimum remaining outgoing queue space rule
    - FIFO
    - LIFO

- Idle vehicle rules:
    - Vehicle stays at the current control point
    - Vehicle travels to a certain control point
    - Vehicle cycles through the system.

• Contention rules:

- FIFO
- Closest remaining distance rule

The proper vehicle initiated dispatching rule is crucial in order to avoid shop locking phenomena (Egbelu and Tanchoco, 1987). Even with a relatively simple layout where few machines and vehicles are involved, the whole system can lock, if the wrong dispatching rule is used. Shop locking can also be avoided with a central buffer, so that vehicles can temporarily unload and be redirected to more pressing needs that, if not satisfied, may lead to shop locking. Another solution is to keep extra vehicles in reserve at some location (presumably at spurs) and have them dispatched when all other vehicles are loaded and shop locking occurs.

V-1.5 Control mechanisms

Control mechanisms do not constitute a set of parameters per se in system analysis, but they play an important role as they make possible the different flexibilities in terms of routing, volume and expansion. It is the control system that makes possible all the above dispatching rules which can be implemented, and therefore the overall operational feasibility of the FMS possible.

Two fundamental types of controls are found within FMS: centralized and decentralized (Lingren, 1987). Though a centralized system seems less complicated and less expensive than its decentralized counterpart, the latter is more appropriate when the AGV layout becomes complex, involving a large number of vehicles and high material flow. Moreover, a decentralized control (such as a distributed net) is better suited for tackling breakdown situations (of the master scheduler) and favors expansion flexibility and dynamic scheduling (Shaw, 1988).

V-2. CONCEPTS OF FLEXIBILITY

The above discussion indicates that parameters involved in the design of FMS/AGVS cannot be examined separately, but that their interdependencies should be acknowledged as well. Layout analyses have traditionally been done in order to minimize transportation costs by minimizing distance between inter-machine flows. However, blocking problems due to the routing of parts may have to be assessed as well as when considering track configuration. Fleet characterization is, a priori, determined by load analysis and the usual transport matrix. But again, layout characteristics and dispatching rules may have an effect on fleet size. Finally, these dispatching rules condition the operational feasibility of the system by avoiding shop locking. However, it appears that this phenomenon can also be avoided by adding vehicles to the minimum fleet size and modifying the layout.

Traditional engineering design of MHS would first look at the routing of parts in order to assess the flow of materials between stations (for a given lead time). Then the layout would be generated. From network and vehicle characteristics, along with overall system load and capacity, the number of vehicles would be determined. Finally, dispatching procedures would be devised to insure proper operations. However, these vehicles may contribute to blocking phenomenon (along with network topology), and therefore, several design variables may need to be modified in a feedback fashion if proper lead time is to be achieved (See Figure 14).

Figure 14 attempts to show how the variables discussed above are intertwined. The relationships described here link the main types of variables associated with AGVS design (namely, routing, layout network, AGV fleet and dispatching procedures). Lead time and throughput are the typical performance criteria for these systems. These can be computed with analytical techniques. However, simulation is likely to be useful to take into consideration dynamic phenomena such as blocking, shop locking and dispatching rules which have an effect on throughput. *Feed back loops* have been added to the main links in Figure 14 to show that analytical techniques are most likely to be supplemented with simulation modeling.

Flexibility indices should be developed with these interdependencies in mind, so as to reflect alternative ways a system may be flexible (and indicate trade offs between variables). It would seem appropriate that they also take into account, to the extent possible, a large set of parameters in order to analyze FMS's in an integrated and systemic fashion.

Flexibilities themselves are likely to be interrelated as well. In sections I.4 and II-5.1.4 , interdependencies between routing and volume flexibilities were suggested. For instance, volume flexibility may be examined with respect to fleet size. On the one hand, not enough vehicles may hinder volume flexibility in the sense that the MHS capacity is insufficient to cover the

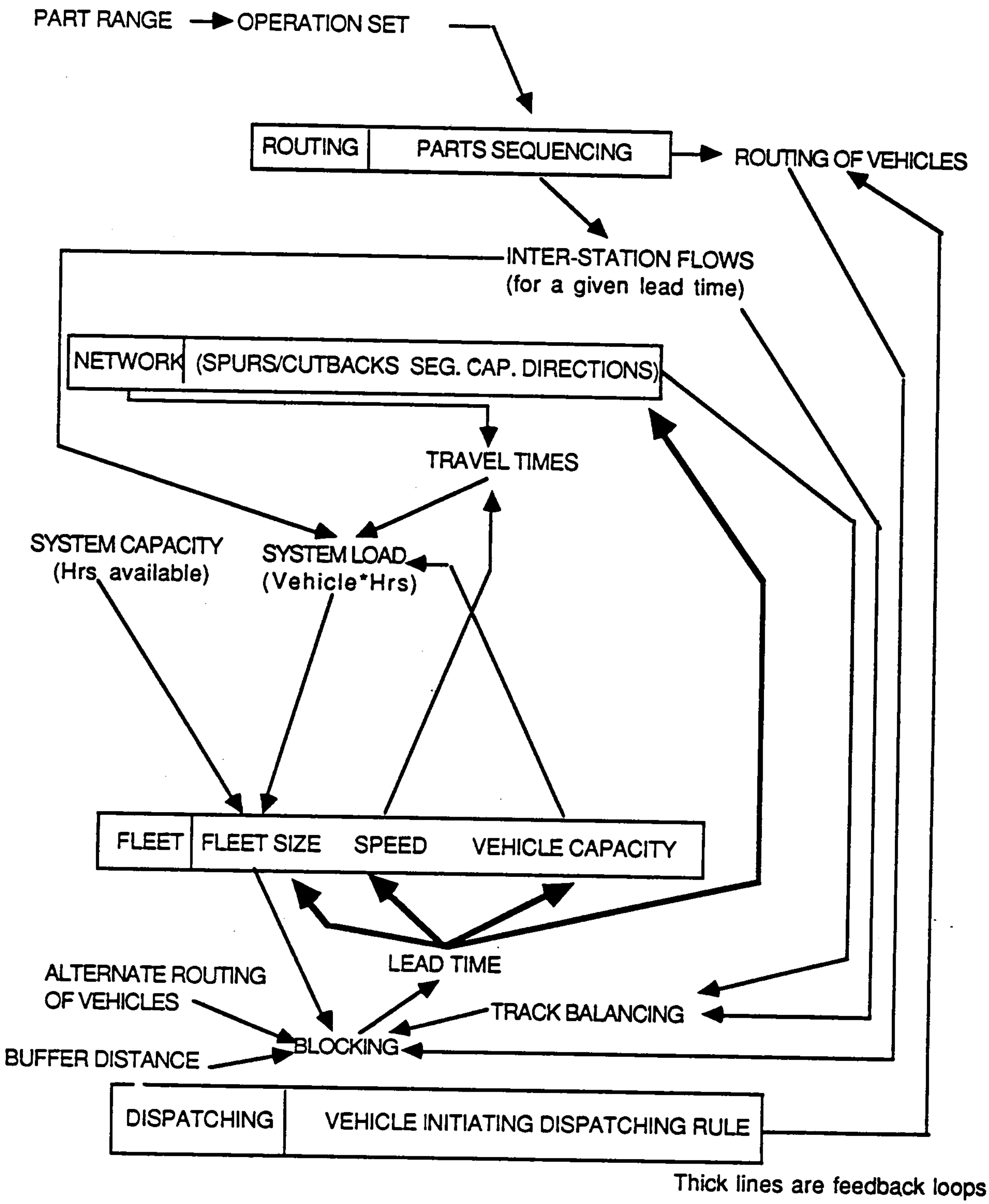


FIGURE 14. INTERDEPENDENCE BETWEEN MAIN DESIGN VARIABLES OF FMS/AGVS (BASED ON MAXWELL AND MUCKSTADT 1987; DAR-EL AND SARIN 1985; TANCHOCO AND EGBELU, 1987)

product demand On the other hand, too many of them may cause blocking. This suggests that, ceteris paribus, there is a fleet size range that could be at the basis of a volume flexibility concept.

V-2.1 ELASTICITY CONCEPTS OF FLEXIBILITY

In section II-4 , it was illustrated that flexibility could be seen from different viewpoints. Being flexible can be a synonym to variety (product range). In this sense, a flexible manufacturing system is one that produces different batches of products *simultaneously* within the same time horizon. Flexibility can be defined as the response time of a system reacting to some internal or external disturbances. Along this line of thinking, flexibility can be construed as the *ability* of a system to respond to a modification of the environment that forces it to change in order to maintain its *effectiveness* and survival. This ability can be measured in the usual way of system response time and product diversification. However, flexibility could also be thought of as the amount of resources or *modifications* needed to perform the necessary changes within the system. For a given disturbance, a manufacturing system that requires numerous and costly modifications would seem less flexible than another one that requires fewer modifications.

Flexibility indices may be thus based on the idea of reaction capability to disturbance. At this point, two aspects of this capability can be defined: static and dynamic. The static aspect of flexibility is concerned with the feasibility of a system to depart from one supposedly steady state to another. The dynamic aspect addresses the problem of how fast the system can reach that new state.

Based on the discussion of the preceding section, the possible disturbances along with responses available to the system are listed below (Δ meaning changes in).

Disturbances:

1. Δ demand (D)
2. Δ product mix (PM)
3. Δ in the number of cells, i.e., cell breakdown (C)
4. combinations of the preceding

Responses:

A. Δ vehicle speed (VS)
B. Δ vehicle capacity (VC)
C. Δ fleet size (FT)
D. Δ buffer distance (BF)
E. Δ routing, i.e., use alternate routes (R)
F. Δ dispatching rules
G. Δ layout, i.e., add spurs, cutbacks (L)
H. Δ segments capacity (SC)
I. Δ number of possible directions (UNI or BI).
J. combinations of the preceding

Three flexibilities were said to be pertinent to MHS within FMS (Section II-4.1, p.18): routing, volume and expansion flexibility. Routing flexibility requires the presence of alternative routes to process a given machine sequence. It also implies the capability of using an alternative machine sequence. (Recall from section II-4.2 that a given operation set could be sequenced in more than one way and, in turn, to one sequence could be associated alternative routings.) Volume flexibility is the ability to operate the FMS for different demand levels. Finally, expansion flexibility is the ability to expand the system either by modifying the layout in a minor way (like adding spurs or cutbacks) or by adding a complete cell which is linked with the appropriate additional AGV track segments (or conveyors). If a material handling system is considered in terms of its layout, its fleet of vehicles (or conveyors), its routings, and its dispatching rules, then its flexibilities can be defined by its capability of modifying one or more of the above parameters in order to respond to inner or outer disturbances.

Another problem related to measuring flexibility is some reference point that acts as a benchmark which can give a better appreciation of how well a system is flexible. A system that can handle a change in demand up to ΔD which represents 100% of the average or initial demand D should be considered more flexible than if the change represented only 50%. Then, as it was mentioned above, this capability to fend off this ΔD should be confronted with the necessary modifications and changes that the system must undergo. If a system requires the addition of twice as many vehicles as another one to counteract the same increase in demand or change in product mix, then the latter should be considered more flexible. Finally, the flexibility of the MHS should be confronted with the flexibility of the cells (or machines) in order to assess whether the former fully exploits the capabilities of the latter. As was pointed out in section II-4.2 , the overall flexibility of the system is a function of the flexibility of the cells and the MHS, which suggests that inflexible cells could be linked with a flexible MHS and still generate high overall system flexibility.

Another assumption underlying this type of index is the measure of performance used when a surge in demand can be handled by a particular response. For example, the measure of performance could be the amount of parts the system can process in a given time period. In other words, how much faster (ΔVS) must the vehicles be traveling, so that the new demand ($D+\Delta D$) can be met on the same deadline (or due date for the whole batch of parts).

Some of these changes mentioned above involve continuous and discrete variables, and for which an optimum value is sought (buffer distance, number of vehicles), while others are more descriptive and combinatorial in nature as they are related to the whole system (dispatching rules, alternate routing). For the first type of variables, it appears to be easy to relate them in a simple mathematical fashion. However, it will be difficult to use a simple quantitative approach when dealing with the second type of variables.

For the first type of variables, an index which is close to the concept of elasticity in economics and which relates disturbances with system response, was developed in this research, and is the following:

$$\text{Demand flexibility} = \frac{(\Delta D/D)}{(\Delta VS/VS)}$$

The numerator indicates the change in demand that can be *handled* by the system, and the denominator is the modification in terms of vehicle speed that is necessary to precisely counteract this presumed surge in demand. It is implicitly assumed here that, for this particular case, other responses (such as adding new vehicles or new tracks) are not necessary.

A more extensive index was formed by including more responses if they are necessary:

$$\text{Demand flexibility} = \frac{(\Delta D/D)}{(\Delta VS/VS + \Delta FT/FT + \Delta VC/VC)}.$$

Here, a change in demand must be met with three system modifications, namely, a change in vehicle speed, in fleet size and in vehicle capacity. When more than one response is possible to counteract a given disturbance, then the problem of chosing among alternative responses arises. If the possible responses could be ordered in terms of their costs, then it would seem to make sense that the least costly would be utilized first, then the next to the least costly response would be used if necessary, and so on. If the ordering criterion of these responses is the time needed to implement them, then a dynamic aspect is included in the indices. Up to now, it was assumed that the changes or responses could be done in a very short period compared to the time required to process all parts.

Similar indices can be formed for changes in product mix, and changes in the number of available cells. Expansion flexibility could be measured by the ability, in terms of costs and time, required to add new cells, if really it is new cells that are required.

Routing flexibility seems to be more difficult to measure, as it involves combinatorial aspects. Routing flexibility is the ability to reroute a part due to machine breakdown. When a cell is no longer available, the parts must be rerouted to other cells or machines. It is assumed that a cell will have its own set of flexibilities that will permit it to absorb an increase in throughput (and a set of new jobs). The question here is that if the remaining cells can take the overload, will the MHS be able to deliver the parts in time without excessive blocking ? It can be intuitively seen that if a cell breaks down, then the flow of material must be redirected to the remaining three cells. This may result in a substantial increase in flow intensity, especially near the loading/unloading stations, if routing requires that parts cycle several times through the system. In addition, if the layout has balanced tracks for a given flow of parts, will it still be balanced with new flow patterns resulting from a cell breakdown ? Therefore, routing flexibility is not only measured by the number of potential (a priori) alternate routes an MHS can use to transfer a given part, but also by the number of *feasible* routings it will effectively be able to use.

In order to analyze the flexibilities of FMS/AGVS, two types of studies can be performed. A time independent analysis where flows are aggregated and seen in a static fashion and a time dependent one where the flow of each part is traced through the system. The first type of analysis can be, in certain conditions, a good approximation to real systems. However, when dynamic phenomena such as blocking and shop locking become predominant, then this last type of methodology is more advantageous.

Several types of FMS can be studied. They can be distinguished primarily with the following parameters:

- The part range to be processed
- The number of operations that each part has to go through
- The sequencing of machines for each of these operations
- The flexibility of the cells themselves
- The presence of input/output buffers at cells

V-2.2 EFFICIENCY AND EFFECTIVENESS CONCEPT OF FLEXIBILITY

In this section, a composite measure of performance, related indirectly to volume flexibility, is developed, so that the phenomenon of throughput increase due to lead time reduction and system overlap can be better assessed. This index called PMHS (percentage of perfect MHS) is in fact an efficiency measure of the AGVS which attempts to determine how close it is to an *ideal* MHS. Another index, related to the effectiveness of that same AGVS, will also be developed and used in conjunction with the PMHS index, so that increases in efficiency can be linked with improvements in system effectiveness. This effectiveness measure is related to the maximum capacity of the FMS/AGVS.

The delays encountered by loads in an FMS are what makes an MHS *imperfect*. These delays typically happen when a load is waiting for a machine to be freed, or is waiting for an AGV to be dispatched, or for an AGV to travel to the desired control point. Additional delays occur because of loading and unloading times. All these waiting times appear to be interdependent as the reduction of one brings the reduction of the others. By increasing fleet size, the time it takes for a vehicle to be dispatched can be reduced. This will have the effect of reducing the time a load waits for a vehicle which, in turn, will reduce the time for a machine to be freed.

The concept of flexibility as it is related to capacity can be linked to the efficiency and the effectiveness of the MHS by incorporating these delays and throughput measures. For a certain type of FMS, a particular pattern of waiting times are imposed on the entities being processed.

Throughput of a system is a function of lead time itself and the degree of *overlap* , that is, the ability of a system to process more than one part simultaneously. An FMS is flexible partly because it can reduce the parts' lead times and because of its overlapping capability. Lead time is basically a function of total machine time and total material handling time. Overlapping depends on the overall operational structure of the FMS which determines the pattern of waiting time mentioned above. An FMS with interstation buffers has a different structure than a system without them.

The efficiency index developed below tends to capture the ability of a FMS to reduce its lead time as modifications are performed on its MHS. In this sense, the lower the material handling time (and thus the lower the lead time), the more efficient is the MHS. A *perfect* MHS is an MHS with zero material handling time. It is therefore possible to measure the closeness of MHS to its ideal (in terms of percent of the perfect material handling system, PMHS) :

$$PMHS = \frac{MT}{MT + MHST} * 100 ,$$

where MT is the overall machine time for one individual load when it is within the FMS itself.

Further, $MHST = TT + LUT + WT$,

where TT is travel time of a load on the AGV;

LUT is total load and unload time for a load (excluding time at the fixturing station);

WT is the waiting time imposed on the load during its sojourn in the FMS.

The waiting time includes waiting for a machine to be freed, and waiting for an AGV to arrive to the control point where the load is stationed. Travel time depends on machine routing, the layout configuration and vehicle speed. If there is more than one routing (presumably the implication of a product mix), then the average travel time is used. This average is weighted by the proportion of part types that are processed by the system. It is assumed here that blocking is minimal.

The total load/unload time mainly depends on the number of machines that a load has to visit in the FMS. This parameter also depends on the technological characteristics of the transfer devices themselves.

The waiting time depends on the layout configuration, vehicle speed, fleet size, and dispatching procedures. It also depends on the presence of interstation buffers.

These components of material handling time are likely to be interdependent as was mentioned above. For instance, reducing travel time may also reduce wait time. Reducing load and unload time may also have a multiplier effect throughout the system, as it reduces waiting time as well.

Another index of performance associated with the MHS is its effectiveness with respect to the overall capacity of the FMS. Assuming that the machines are not the bottleneck, then any improvement in throughput will result in improvement of the MHS.

This effectiveness index is simply in terms of percent of capacity (PCP):

$$PCP = \frac{THROUGHPUT}{CAPACITY} * 100 .$$

The capacity of the FMS is the maximum throughput when the MHS is pushed to its limits by increasing the number of vehicles and speed parameters to the extent possible.

V-3. SUMMARY

The analysis of AGVS has shown that the variables involved in AGVS design are numerous and are interrelated in a network fashion. The design of these systems can be made with analytical techniques, but simulation must be used as well for variables such as dispatching rules and for dynamic aspects such as vehicle blocking and shop locking. Among the most important performance criteria for evaluating AGVS from a system perspective are throughput, lead time, fleet size, system load and system capacity.

Two types of flexibility indices were developed. One type was based on the concept of resiliency of a system facing internal and external perturbations. This type of index was related to, among other things, system throughput. The second type of flexibility index was based on the concept of closeness to an ideal MHS and was related to lead time and overlap.

VI-FLEXIBILITY: OPPORTUNITY COSTS AND ECONOMIES OF SCOPE

In this chapter, theoretical underpinnings pertaining to the evaluation process and flexibility indices, as they are used in this research, are presented. Two major aspects of the evaluation problem are thus explored: opportunity costs and economies of scope. In this research, opportunity costs are mainly opportunities forgone due to insufficient throughput or product range by not investing in flexible systems. Therefore, this aspect of the evaluation problem is concerned with the demand side of differentiated products. Economies of scope deals with the economics of these FMS. This aspect is concerned with the fact that the cost of producing, for instance, two products on a flexible machine is lower than producing each of them on specialized machines. The first section describes the problem associated with opportunity costs and flexibility indices. The second deals with operational costs and economies of scope as they are related with the optimal flexibility level of an FMS. In this research, these flexibility indices have three roles within the evaluation frameworks. First, they help compare alternatives from a purely technical aspect. This particular application will be demonstrated in Chapter VIII. Second, they are used in the multiattribute framework developed in Section VII-2. Finally, they are likely to help establish the kinds of opportunity costs that are involved in a particular situation.

The indices presented here are the ones developed in this dissertation. In particular, this research concentrates on the elasticity indices and the ones associated with efficiency and effectiveness.

VI-1. FLEXIBILITY INDICES AND OPPORTUNITY COSTS

A major assumption which is implicit in the literature regarding evaluation of new manufacturing technologies is that the decision maker knows precisely, or can estimate, the probability of the opportunity costs associated with a given level of flexibility. Furthermore, it is assumed that a certain relationship between flexibility and opportunity costs can be formulated in the following way:

Opportunity Costs = F(Flexibility) .

The function "F" is assumed to exist and can be estimated (at least for some points or for some range pertinent to the prevailing situation) by the decision maker in a deterministic or stochastic fashion. This relation is mainly a starting point to the evaluation framework described in the next chapter.

The above formulation of the relationship between opportunity costs and flexibility is very general and can be specified furthermore:

Opportunity Costs = F(RF, VF, EF) ,

where RF is routing flexibility, VF is volume flexibility, and EF is expansion flexibility.

It will be assumed furthermore that each of these flexibilities can be estimated by indices:

RF = f_R(n, blocking, resilience to routing changes),

where n is the product range and "blocking" is a measure of congestion for a given layout (and a given throughput). Resilience to routing changes is essentially a measure of the MHS to maintain its performance level (throughput) when routing is modified. Such disturbances are likely to be caused by new product mixes or machine breakdown.

VF= f_V((ΔTH/TH)/(ΔFT/FT), (ΔTH/TH)/(ΔV/V), TH/CAP , PMHS)

where (ΔTH/TH)/(ΔFT/FT) is the ratio of the change in throughput resulting from a change in fleet size; (ΔTH/TH)/(ΔV/V) is the change in throughput resulting from a change in vehicle speed; TH/CAP is the ratio of throughput to system capacity; PMHS is a measure of how close the material handling system is to an *ideal* MHS. This type of measure was developed in Chapter V.

Finally,

EF= f_E(cost of change, time required for modifications)

This last flexibility has to do with how easily the MHS can be used to expand the system.

Another simplifying assumption is that these flexibilities are in a additive relationship:

Opportunity Costs = $f_R + f_V + f_E$.

This last hypothesis is an approximation that will be useful in designing the evaluation process. It should be noted however that flexibilities are not likely to be independent of one another. For example, an increase in volume flexibility may be beneficial for routing flexibility as well. Such interdependencies are explored in Chapter VIII.

If the above functions cannot be estimated, then the flexibility indices would still be used in comparing alternative systems or variations of a basic configuration. In this case, the analysis would mainly be of a technical nature. The economic aspect comes into the picture when those opportunity costs (along with the economies of scope) are estimated.

Lost sales is the typical link between opportunity costs and flexibility indices. To an *insufficient* throughput or product range are associated lost revenues that could have been reaped by the organization, if it had invested in flexible manufacturing technologies. The more flexible a system is, the less opportunity costs it will incur. Therefore, the flexibility indices and opportunity costs should be in an inverse relationship: the higher the index, the lower the opportunity costs.

Not all indices are likely to be used by the decision maker. Depending on the prevailing situation, a particular flexibility might be more important than others. AHP frameworks are suggested in Section VII-2.2 in order to determine the ranking of these flexibilities so that the most appropriate index can be chosen.

Once opportunity costs are estimated, then other costs can be assessed. Such costs are associated, among other things, with operational aspects of the manufacturing system. The next section looks at these costs from a theoretical point of view. Practical considerations concerning these costs are explored in Section VII-1.

VI-2. ECONOMIES OF SCOPE

Theoretically, when flexibility is an important characteristic in manufacturing systems, then economies of scope predominate over classical economies of scale. These result mainly from flexible machines within FMS (integrated with its MHS) that gives the overall system the ability to produce a large part range enabling the organization to profit from product differentiation. Talaysum, et al,(1986) have proposed that in such a case the production function used to conceptualize the system is:

$$CQ = g(CK, ME) ,$$

where CQ is the composite output of the system (a weighted sum of all products manufactured by the system); CK is capital and labor, and ME is a variable grouping energy and material. If such a relationship could be determined for a manufacturing system, then an optimal composite output, CQ, could be found in the same way that an optimal scale is found within a classical production function. More precisely, the above function implicitly defines a region for which the addition of new products is advantageous from a cost point of view (increasing returns to scope) and a region for which further addition is not advantageous (decreasing returns to scope). In other words, increasing returns to scope means that composite output increases at an increasing rate when variety increases. Decreasing returns to scope means that composite output increases at a decreasing rate as variety increases (Talaysum, et al, 1986). In terms of costs, this means that marginal costs decrease as variety increases in the region of economies of scope, and increase in the region of diseconomies of scope. The implication of this analysis is the likelihood of an optimal scope or range for which average operating costs is minimized.

However, these returns to scope might be difficult to assess, simply because the function CQ may be impossible to determine. Therefore, analytical techniques and simulation of FMS are likely to be helpful in estimating these costs.

This chapter has presented two fundamental aspects of new manufacturing technologies which, though theoretical, are likely to have practical impact on the evaluation of material handling systems within FMS. First, opportunity costs were construed to be a function of the system flexibility and, in particular, of flexibility indices which indicates the nature of these costs (lost sales, insufficient product range, long lead time, etc.). A further assumption was that to each of the flexibilities involved was associated a certain type of opportunity cost, and that each of these costs could be added to the other in order to have an overall estimate of the type of cost. This theoretical development was used in the evaluation frameworks (Chapter, VII). Second, the theoretical concept of economies of scope operations costs showed that operations costs are to be carefully measured if, for example, multi-purpose machines are used. This aspect does not pertain to MHS per se. However, an MHS may have the effect of fully exploiting those economies of scope as for example, when the product mix increases.

VII-THE EVALUATION PROCESS

VII-1. DECISION FRAMEWORKS

In this chapter, frameworks that integrate the aspects of evaluation of AGVS discussed previously are presented. They are an attempt to make the overall evaluation process of these systems systematic by generating alternatives which are improvements over the preceding ones. They also attempt to structure the analysis of AGVS within FMS (See Figure 15). Another type of framework combines the AHP and the DIM for the interdisciplinary aspect of the evaluation process.

The processes proposed here are essentially recursive and generate an alternative at each iteration. Each of these processes starts with a current system which can be an FMS with conveyors, AGVS, or a system comprised of cells that are yet not linked by any MHS. The idea is to modify the current system by adding or replacing some parts with new AGVS components. The impact of these changes would be assessed from a technical viewpoint (increase in capacity for example). At this point, the modification can produce one of two main results (apart form changes in operational costs): there is an improvement in terms of flexibility (capacity), or there is no improvement. In the case of no improvement, the new system is still of interest, since its cost may be lower than the preceding one. For example, a small fleet size of fast vehicles may be less expensive than a large fleet of slow vehicles for a given capacity. Therefore, it is interesting to look at different combinations of AGVS, since one of them may minimize cost. If there is an improvement in terms of flexibility resulting from the change, then the cost of that change is to be assessed. Depending on the type of change imposed on the system a certain number of costs will be incurred. These costs can be due to the introduction of new equipment (first costs), labor and maintenance (operating costs) and costs due to the current change itself imposed on the system. Then, opportunity costs are assessed. These can be estimated by the reduction of lost sales due to the increase in volume flexibility (capacity) or due to the fact that the new system can process a broader part range. At this point, trade offs between those opportunity costs and costs due to changing the system can be evaluated.

This procedure is repeated until the decision maker has a *sufficient* number of alternatives to deal with. By sufficient it is meant that the decision maker feels he has covered enough cases so that he can proceed to the choice of the optimal alternative, that is the one which minimizes change and opportunity costs (as well as all other costs). In order to compare a large number of alternatives, from a throughput point of view or volume flexibility, the index developed in the previous chapter (which relates the possible response of a system to an environmental perturbation) can be used.

The process has assumed a one period framework. However, the set of alternatives generated by the process can be considered as steps in a multi-period framework where each step is an improvement within a global investment plan. Investing gradually in new manufacturing technology may be a sound strategy in the face of future uncertainty, or simply because of budget constraints. A decision maker could therefore examine different *patterns* of improvements over time. He could, for example, consider a strategy where there are heavy changes at early periods and fewer changes afterwards. Inversely, another strategy would call for small changes at the beginning and wait for more substantial ones in the future. The preferred strategy would probably depend on the degree of risk averseness of the decision maker toward those opportunities forgone by not investing in flexible systems. Another problem associated with this particular multi-period problem is the length of time between decision points. These decision points are review points where the decision maker assesses the current situation in order to make a new improvement. If the frequency of those changes are too high, then the repeated costs due to modifying the system over time may outweigh the benefits of improvement. If few changes occur, that is, if decision points are too distant, then opportunities forgone by not changing sufficiently in time may be significantly high. This aspect will be discussed in Section VII-8.

So far, three types of MHS flexibilities have been associated with those opportunity costs: volume, routing and expansion. Volume flexibility has been associated with the ability of a system to increase its capacity by modifying it. Routing flexibility is more complex, as it comprises at least two components, namely, the part range and the ability to absorb an increase in system load in the case of routings which necessitate longer distances traveled by the AGVs within the FMS. In other words, the issues pertaining to this type of flexibility are: 1. Is the system capable of processing the desired product mix ? 2. If it can, how well can it do the job in terms of throughput for each of these products ? Another aspect of this flexibility is the capability of a particular layout to minimize blocking when the fleet size is relatively large. It will be seen later that a ladder type FMS exhibits less blocking than the single loop type FMS (Section VIII-9). Finally, expansion flexibility is measured by the cost of (future) changes and the time it takes to do these changes. This flexibility is concerned with the capability of the FMS to adapt to unforeseen events in the future. The decision frameworks developed below attempt to integrate these flexibilities.

Figure 15 shows a very simple framework involving a production system manufacturing one product and where one type of flexibility is considered and is tied directly to system capacity. At this stage, only one type of change is involved and pertains to the AVGS fleet itself. Here the decision maker can increase fleet size, substitute the current fleet with another with higher speed, or with higher capacity. Combinations of the preceding could also be done. For example, instead of changing the whole fleet, the decision maker could add or change one or more vehicles with higher speed or capacity (thus electing for a mixed fleet of vehicles) in order to satisfy a peak demand. In the next framework, another type of change is introduced as a refinement of the process. This second type of change includes the following: add spurs and cutbacks, modify the machine layout, add input/output buffers, improve the efficiency of transfer devices (linking the primary and secondary MHS), replace conveyor segments with AGV tracks, change the navigation system.

Several types of costs are incurred when these changes occur. They are classified the following way:

- Increase in first costs:
    - Vehicle cost
    - Guidance system cost
    - Control system cost
    - System integration cost
    - Commissioning and bebugging
    - Floor preparations

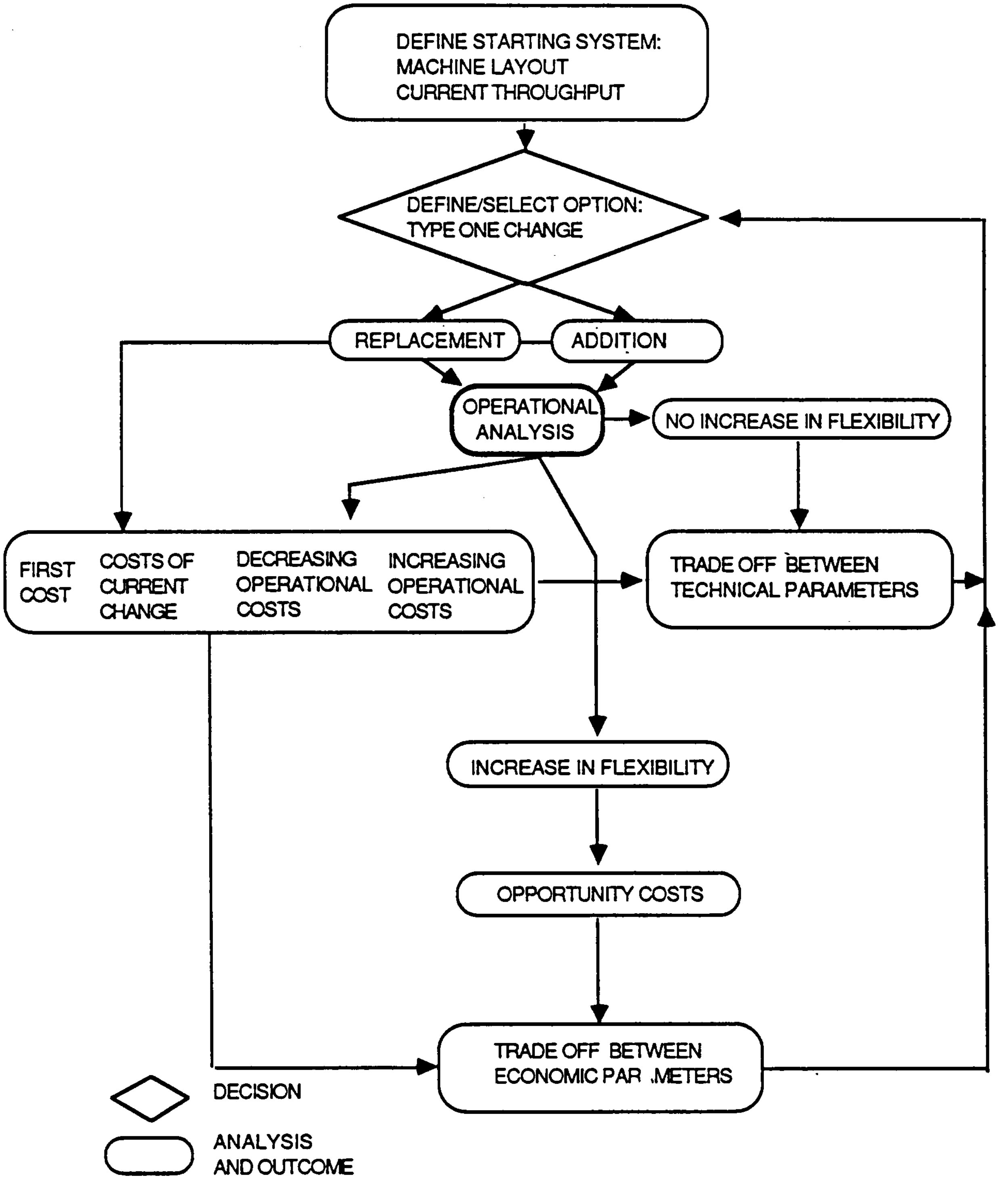


FIGURE 15. EVALUATION FRAMEWORK FOR ONE PRODUCT; ONE TYPE OF CHANGE; ONE TYPE OF FLEXIBILITY

- Increase in operational costs (transportation costs):
  - Direct maintenance costs (salaries, wages, materials and outside services)
  - Indirect maintenance costs (costs arising from downtime)
  - Energy costs

- Decrease in operational costs (transportation costs):
  - Labor savings
  - Space savings
  - Reduced material damages

- Costs of present changes:
  - Cost of retirement of old components
  - Cost of maintenance training
  - Cost due to delays/interruptions
  - Cost due to resistance to change

- Decrease in opportunity costs:
  - Volume flexibility: Increase in throughput.
  - Routing flexibility: Increase in part range. Resiliency to routing changes.

- Expansion flexibility (cost of future changes):

    - Decrease in future layout change costs.
    - Decrease in future layout change time.

Figures 16 to 19 illustrate variations of the basic evaluation process shown in Figure 15. Figure 16 is almost the same as the preceding one, except that the idea of overlap which contributes to throughput increase, as well as lead time reduction, has been added. As will be illustrated in the next chapter, volume flexibility (measured by system capacity) can be improved by either reducing the time each part spends in the FMS or by being able to process more parts simultaneously according to the type of changes that are imposed on the FMS. Figure 17 introduces another type of flexibility, namely, routing flexibility, which is measured by part range. In this case, it is assumed that a particular change will affect either or both flexibilities. Each of these flexibilities will presumably contribute to opportunity cost reduction. Figure 18 is a framework which includes the third type of flexibility, expansion, which like the others is likely to reduce opportunity costs as well. The next figure (19) depicts a substantially different paradigm of the evaluation process. Provisions are made here for the presence of trade-offs between flexibilities in order to discriminate among production systems that would, for instance, exhibit high volume flexibility and low routing flexibility with systems that would exhibit the inverse. This framework (described in a previous chapter) is the most extensive one, as it includes strategic, technical and economic considerations simultaneously and

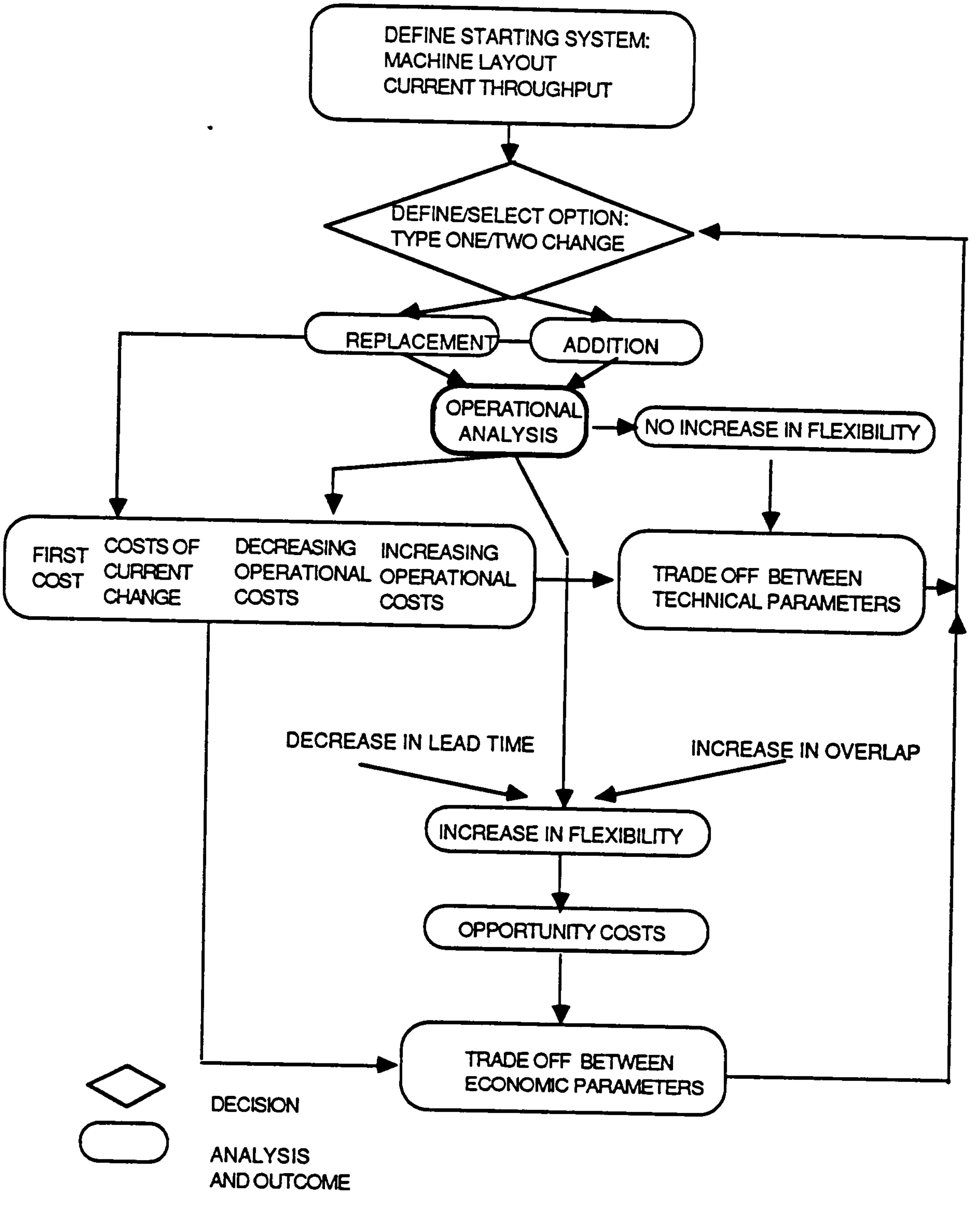


FIGURE 16. EVALUATION FRAMEWORK FOR ONE PRODUCT
TWO TYPES OF CHANGES; ONE TYPE OF FLEXIBILITY

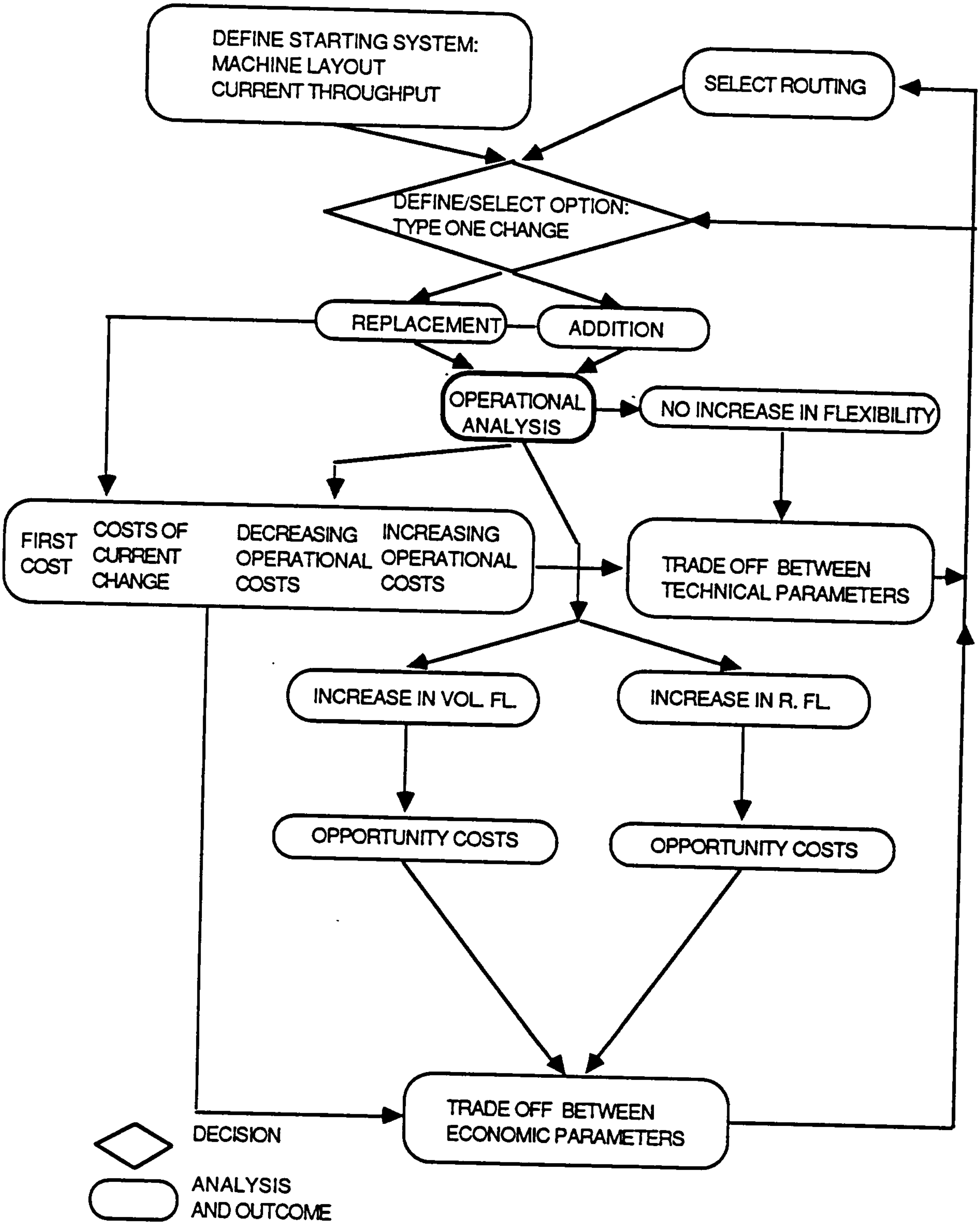


FIGURE 17. EVALUATION FRAMEWORK FOR A PRODUCT MIX
TWO TYPES OF CHANGES; TWO TYPES OF FLEXIBILITY

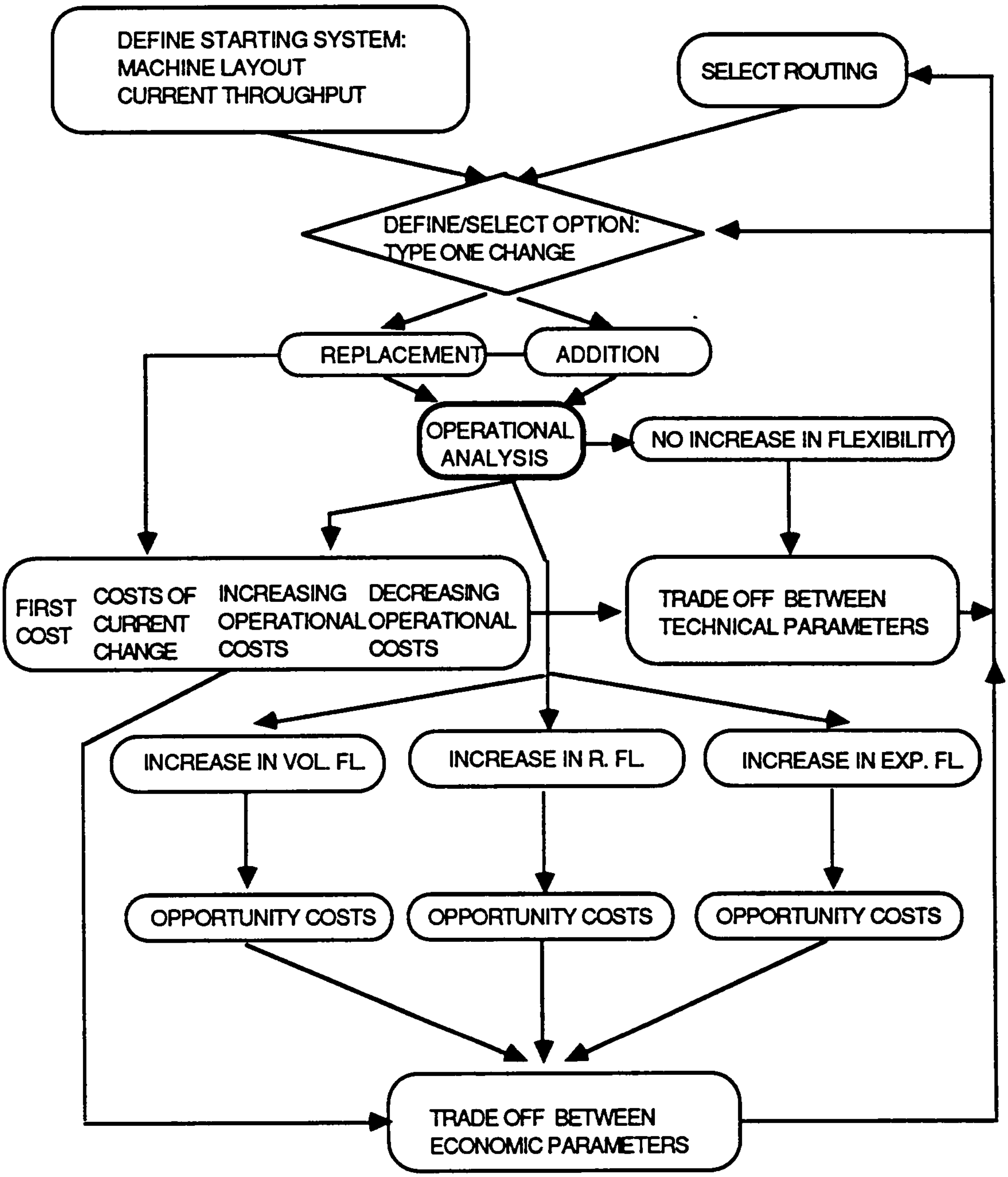


FIGURE 18. EVALUATION FRAMEWORK FOR A PRODUCT MIX
TWO TYPES OF CHANGES; THREE TYPES OF FLEXIBILITY

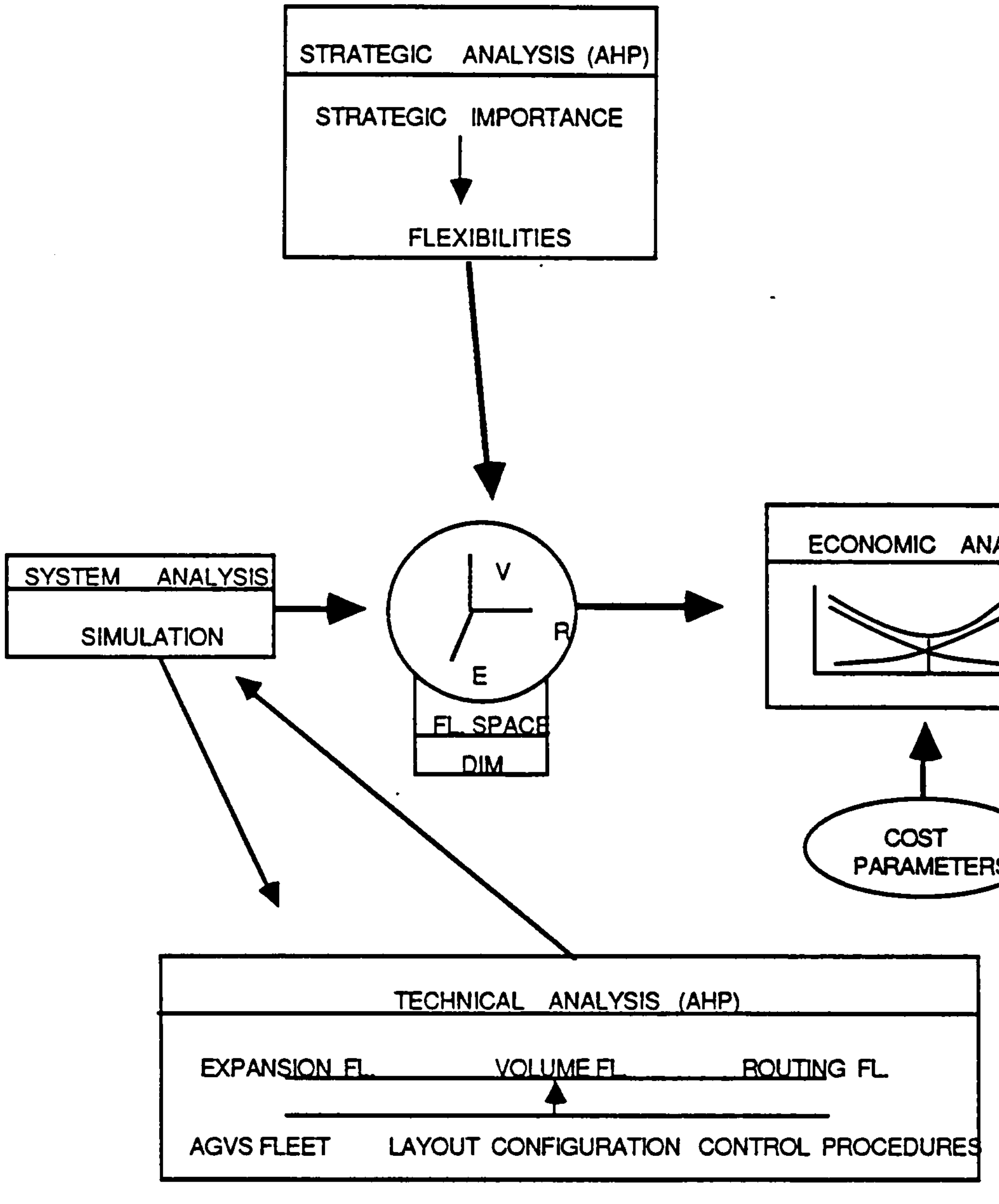


FIGURE 19.EVALUATION FRAMEWORK FOR A PRODUCT MIX; WITH TRADE OFF BETWEEN FLEXIBILITIES

includes the use of the AHP and DIM for multi-attribute considerations.

VII-2 A DECISION FRAMEWORK WITH THE AHP AND DIM

The methodology of this particular framework has been designed so as to integrate more than one aspect of the evaluation process. This framework has also been designed for the case when flexibilities are in a trade-off relationship from a technical point of view.

A technical analysis of material handling would be first undertaken in order to have better understanding of the variables involved. A second analysis, made in parallel with the first one, would look at materials handling systems as imbedded in a larger system, namely, a production system. These two analyses would lead to the use of indices for routing, volume and expansion flexibilities (which would at this point constitute the components of a three dimensional vector of flexibility). A third analysis, more succinct, done from a more organizational or managerial aspect, would attempt to indicate how each of these flexibilities may affect strategic goals of a firm. Such analysis would also indicate which flexibility type is more important than the others with respect to a particular strategic goal. At this point it would be possible to integrate these flexibility indices into one overall index of flexibility for a hypothetical material handling system. Finally, an economic analysis of materials handling systems would be done with first costs, operating costs and opportunity costs expressed by that overall index.

A flow chart of the overall decision process is given in Figure 20. The steps necessary to reach the objectives underlined by these analyses are proposed to be the following:

Technical analysis

1. Gather technical information about material handling systems so as to determine the most important variables that influence their performance. Systems to be examined are the ones typically found in FMS and most likely to fulfill FMS requirements. These are AVGS, conveyors, and robots. In particular, the technical aspects that affect flexibility, can be examined in the case of conveyors (AGVS have been already studied elsewhere in this research) . Examples of these are (Jones, 1987):

- speed
- the capability of diverters
- automatic id. for load detection, routing and control
- capacity ranges
- the capability of lift gates
- the portability of sections (layout reconfigurability)
- the fact that multiple conveyor levels are possible
- the fact that bidirectional travel is possible
- the telescoping capability of conveyors
- the ability of load to be rerouted to another cell.

2. Determine the most important variables (gleaned in the previous step) affecting each flexibility type (routing, volume, expansion).In order to understand what technical variables may affect these flexibilities, specific hierarchies are used (on a qualitative basis). Look at common variables that affect flexibility. Determine the extent to which flexibilities are in

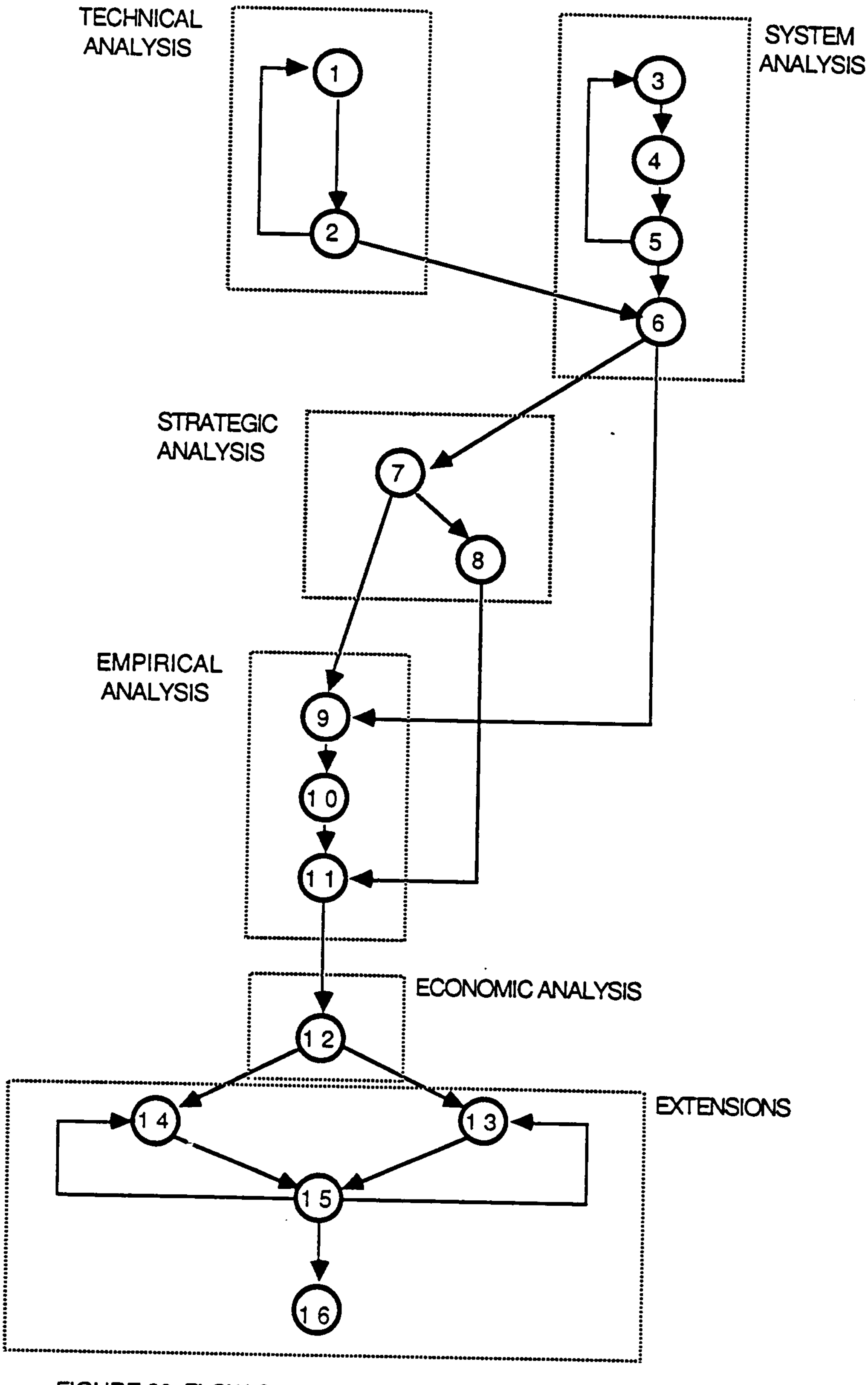


FIGURE 20. FLOW CHART OF DECISION FRAMEWORK WITH THE AHP AND DIM

conflicting relationships. Determine those technical variables from which conflicts arise.

System analysis

3. Choose a particular layout (loop, ladder, open field) with hypothetical cells defined in terms of their cycle time, set up time, and part types.

4. Choose sequences of operations for a given set of parts.

5. Transform the layout into a graph and/or network where the nodes represent workstations and the arcs (directed to show sequence of operations) , represent the flow of materials.

6. Use the flexibility indices pertaining to these material handling systems developed earlier.

Strategic analysis

7. Link strategic parameters of MHS to these indices. (Start building the framework using the AHP).

8. Integrate the AHP and the displaced ideal approach (complete the framework).

Empirical analysis of MHS and integration

9. Choose a set of material handling systems of a certain type. Define specific ranges for parameters such as speed, capacity, etc, and start with a small set of MHS that fall within these ranges. Compute flexibility indices for each MHS alternative.

Convert these into a common closeness scale and position each MHS in a *flexibility space*.

10. Compare MHS alternatives in terms of their flexibilities and examine trade offs between them.

11. Build an overall index of flexibility using the integrated framework.

Economic analysis

12. Examine possible trade-offs between first costs, operating costs and opportunity costs (the value of flexibility) with the overall flexibility index. These costs were defined earlier for AGVS.

What follows are extensions that could be made if networks have been used in the previous steps.

Extensions of the model

13. Expand the analysis with multiflow line that is a production system that produces more than one part or product.

14. Expand the MHS alternatives and include other types of MHS.

15. Re-assess alternatives (in terms of trade-offs).

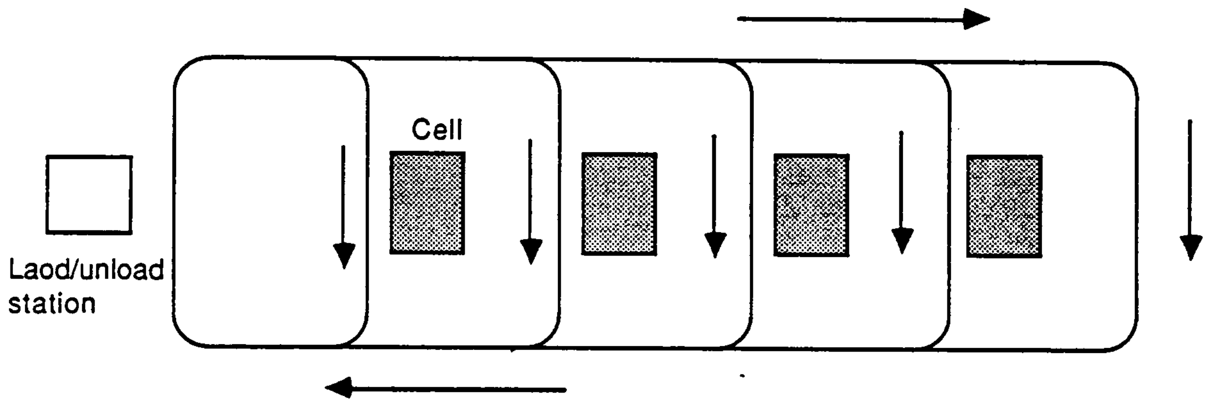
16. Complete framework to the extent possible.

Additional remarks concerning some of these steps are made below.

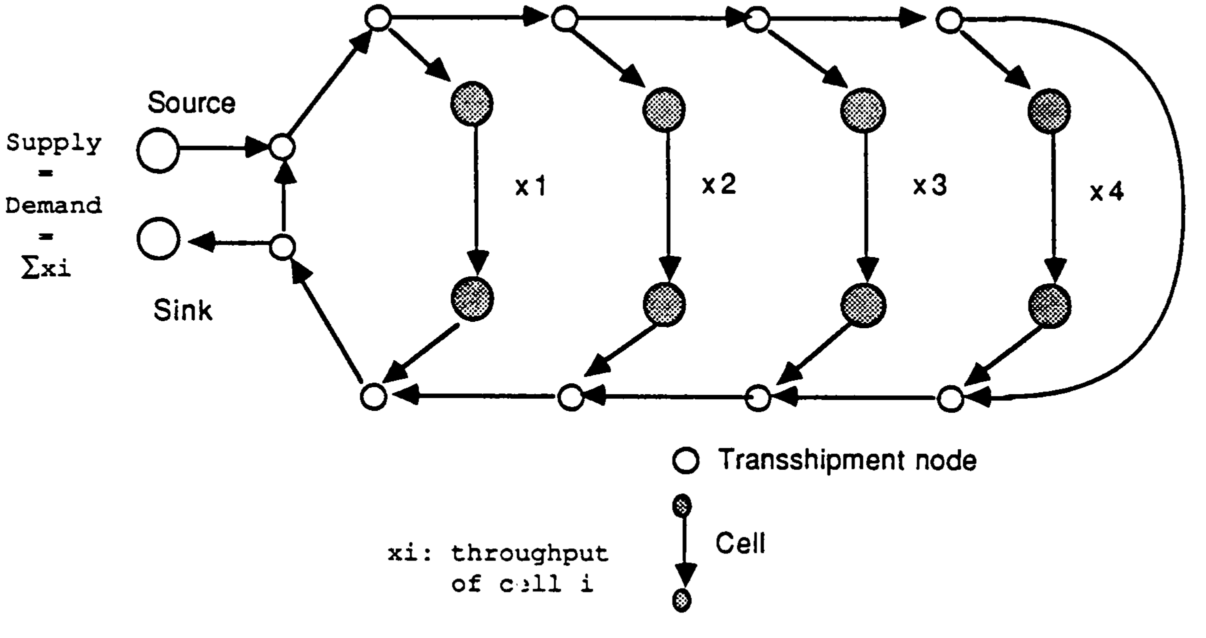
VII-2.1 System Analysis

This part of the analysis can be done with the network models and with simulation. In this case, further remarks on network flows are made here to highlight other types of problems encountered in FMS analysis.

As described earlier, the indices pertaining to material handling systems can be developed using graphs and networks that model the flow of materials between cells or work stations. These graphs are built from the layout (describing the spatial relationships) of the system as well as the sequence of operations (indicating the direction of the arcs within the graph) in the assembly of parts or products. The indices can be determined as a function of shortest paths and maximal flow calculations. The multi flow case can be handled with multi commodity graphs and networks. In Figure 21, a network is shown that models an FMS (whose layout is of the ladder type). The arcs represent the path between workstations. Junctions are represented by transshipment nodes. Each workstation has a pair of nodes linked with an arc whose flow is fixed by the amount of parts or products that need to be processed (within the required time period). Finally, the loading and unloading workstation is represented by two nodes, one of which acts as a source node and the other as a sink node. It would be assumed here that demand is equal to supply (the number of parts entering the system is the same as the number leaving it). The sum



a. A ladder layout



b. Ladder layout network

FIGURE 21. LADDER LAYOUT

of the flows going through each workstation (pair of nodes) would also be equal to the overall demand. (See Figure 21.)

This type of framework may help in examining the effects of machine breakdown, change in capacity of a particular material handling system, and the addition of cells. A machine breakdown may be modeled by deleting its entering arc. Volume flexibility would correspond to modifying the capacity of the arcs. Finally, expansion flexibility may be modeled by the addition of pairs of nodes and perhaps the necessary contiguous arcs. Interdependence between these flexibilities will also be examined; in particular, the effect of expansion flexibility on volume flexibility and the effect of the latter on routing flexibility.

VII-2.2 Strategic Analysis

AHP frameworks were suggested for evaluating flexibilities of materials handling systems (especially AGVS and conveyors) with respect to strategic goals as they emerge within FMS (Figures 8 and 9). Two other frameworks are suggested here that link material handling systems directly to those strategic goals, thus eliminating the need to use the displaced ideal model. The advantage of these hierarchies is that only one multi-criteria technique is used here (namely the AHP). However, these hierarchies are quite extensive to analyze and a great deal of pairwise comparisons are required.

Figures 22 and 23 are examples of such potential models. In Figure 22, AGVS and conveyors are compared with respect to several aspects of performance including economic, technological and flexibility parameters integrated in a five level hierarchy. In this example,

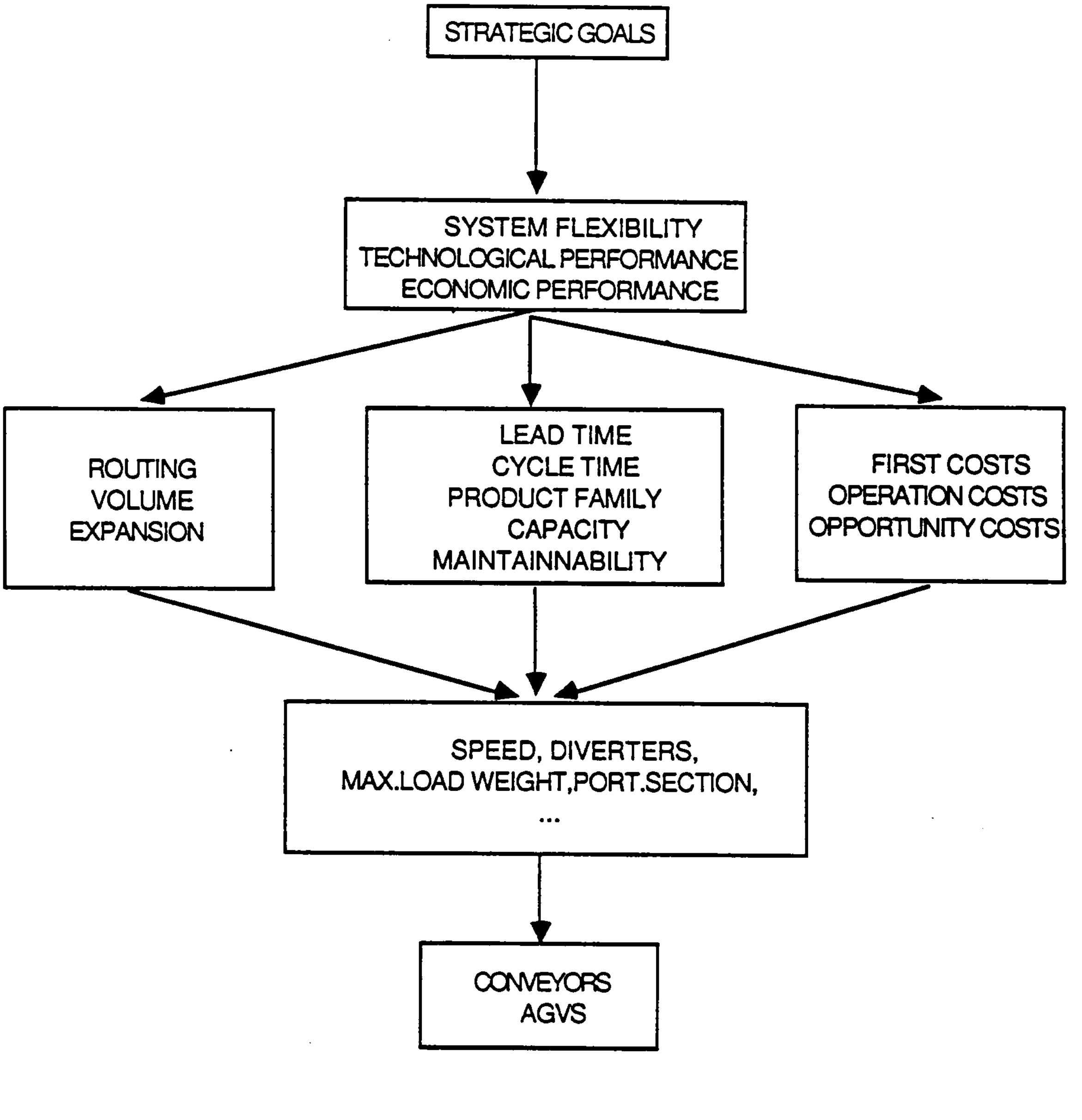


FIGURE 22.SAMPLE HIERARCHY FOR MATERIALS HANDLING SYSTEMS

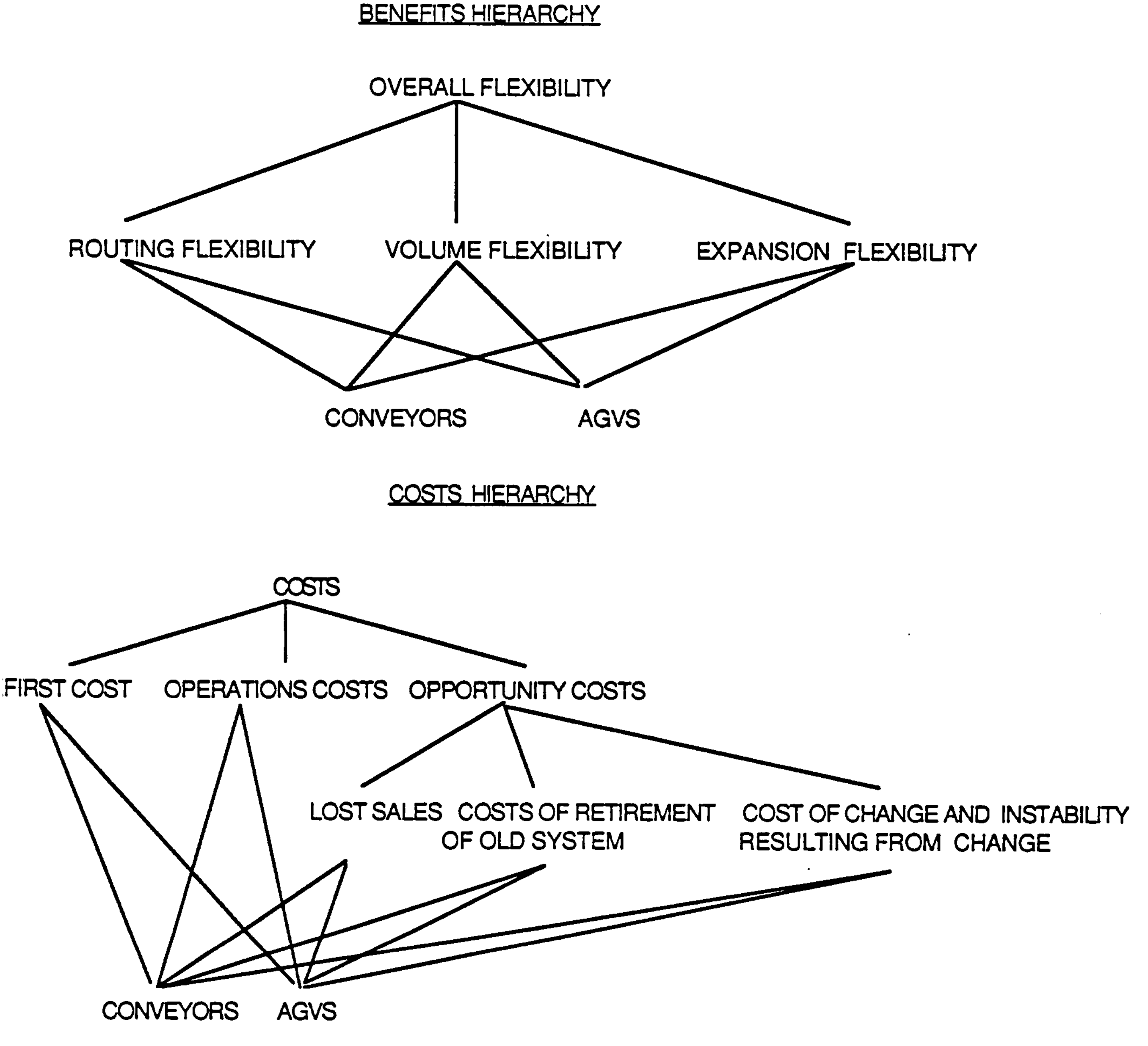


FIGURE 23. COST/BENEFIT APPROACH FOR EVALUATING THE VALUE OF FLEXIBILITY

quantitative data might be combined with qualitative judgements. The latter is likely to occur at the top of the hierarchy where strategic considerations cannot be easily quantified. Technical parameters such as speed and capacity can be used in the hierarchy when properly scaled. Finally, flexibility indices developed for routing , volume and expansion capabilities associated with the various material handling systems would be used. These indices, technical data and qualitative judgements would thus be integrated in one framework that would serve as a decision tool for the evaluation of the alternatives with respect to overall strategic goals.

The second model (Figure 23) is a benefit cost approach where two hierarchies are used to compare the MHS's. The costs hierarchy is more concerned with the value of flexibility represented by the opportunity forgone (in terms of flexibility) associated with each conveyor and AGVS. Again, these hierarchies can be used instead of those presented in Figures 8 and 9. However, the latter ones are more straightforward and can be readily combined with the displaced ideal model.

VII-2.3. Integration

If the DIM is used by the decision maker, then the flexibility indices developed are to be transformed into a closeness scale, d_i^k , so that MHS alternatives may be evaluated and compared with each other (within the displaced ideal framework). The reader will recall the discussion of the DIM in Section II-4.2. The overall weights, λ_i , of each of the flexibilities are determined by how alternatives are scattered in the flexibility space (by using the contrast intensity function, β_i , which yields a posteriori weights), and by their importance in the face of strategic issues. The a priori weights, ω_i , are determined by using the AHP that links operational characteristics of the MHS with strategic goals. The overall weights will be obtained by combining those a priori and a posteriori weights. The integration of the two multicriteria approaches, namely the AHP and displaced ideal model, will result in a decision support process that can handle both quantitative and qualitative variables and include structural and functional dependencies.

Once the overall weights are determined, then an overall index of flexibility can be computed. This aggregated measure of flexibility may then be included in a cost space with other costs (such as first and operating costs), so that trade-offs between them may be assessed.

VII- 3. THE IMPACT OF CHANGES OF MHS ON THE OVERALL FMS

As was mentioned in the previous section, a change imposed on an FMS may have no effect on flexibility of the system but may reduce operating costs, or it can improve flexibility while increasing these same costs. In the first case, several trade offs among options can be examined: 1. trade-offs between first costs (high speed vehicles versus low speed vehicles), 2. trade-offs between first costs and operating costs, since options could have high investment costs and low operational costs, while others could have lower investment cost but higher operational costs, and 3. trade- offs between first and operational costs on the one hand, and cost due to present changes on the other. This last trade-off is less obvious, since a complex system that is costly to procure may well be expensive to install. The second case (alternatives that increase flexibility) leads to trade-offs between first costs, operating cost of present changes , and opportunity costs (which include the cost of future changes).

One problem when evaluating these trade-offs is estimating operational costs when parts or components of systems are replaced. Another problem is that a change in the material handling system may have an impact on the economic performance of the cells themselves. In one multi-machine replacement model (Leung and Tanchoco, 1987) , changes in machines or cells have an effect not only on the cost of machining parts, but also on transportation costs which pertain to the AGVS. This is due to the fact that a change in machines may redirect the flow of material because of technological constraints (in particular, the flexibility of the machines themselves), and because the set of new machines is likely to redirect the flow of parts in a way to minimize processing and transportation costs.

Conversely, a change in the MHS may have an effect on the transportation costs which in turn may change the optimal flow pattern. For example, a change in layout may modify distances between machines or cells which in turn may modify the overall pattern of flow between these machines. An increase in fleet size is likely to increase maintenance and energy costs associated with AGV operations incurred in running the fleet of vehicles, which again will increase transportation unit costs. This may have an effect on the optimal flow pattern.

In other words, a thorough analysis of the effect of changes of MHS on the operational costs of an FMS/AGVS should take into account cost parameters pertaining to machines or cells themselves, which consume resources such as labor (direct and indirect), energy and maintenance. These operational cost parameters can be included in the overall decision process by programming the proper computations within simulation runs or with the use of analytical techniques or both.

VII- 4. OPERATIONAL ANALYSIS OF AGVS

In order to make the evaluation process more detailed, analytical frameworks by Leung, et al, (1987) and by Maxwell and Muckstadt (1987) will be used. Changes in operational costs resulting from modifications performed on the system can be seen with such models. However, a simulation procedure could also be used. In this later case, the program would compute costs while simulating the FMS, as resources (machines and MHS) are consumed by parts being processed. However, analytical techniques are useful because of their relative simplicity and their ability to show the interaction between variables.

Figure 24 illustrates an analysis procedure where analytical techniques and simulation are combined. As was said earlier, analytical techniques are associated with static models of AGVS, while simulation includes dynamic aspects such as dispatching and congestion. In the next section, analytical techniques that can be used in such a process will be described. The simulation aspects will be described in the next chapter with examples of FMS.

The analytical techniques involved in the analysis procedure are essentially network flows that model the overall throughput pattern of parts within the system. The main hypothesis underlying this particular process is that the decision maker, while selecting an option, attempts to: 1. increase throughput as much as possible, and 2. minimize, given this throughput, operational costs through the rearrangement of flows within the network (if that is

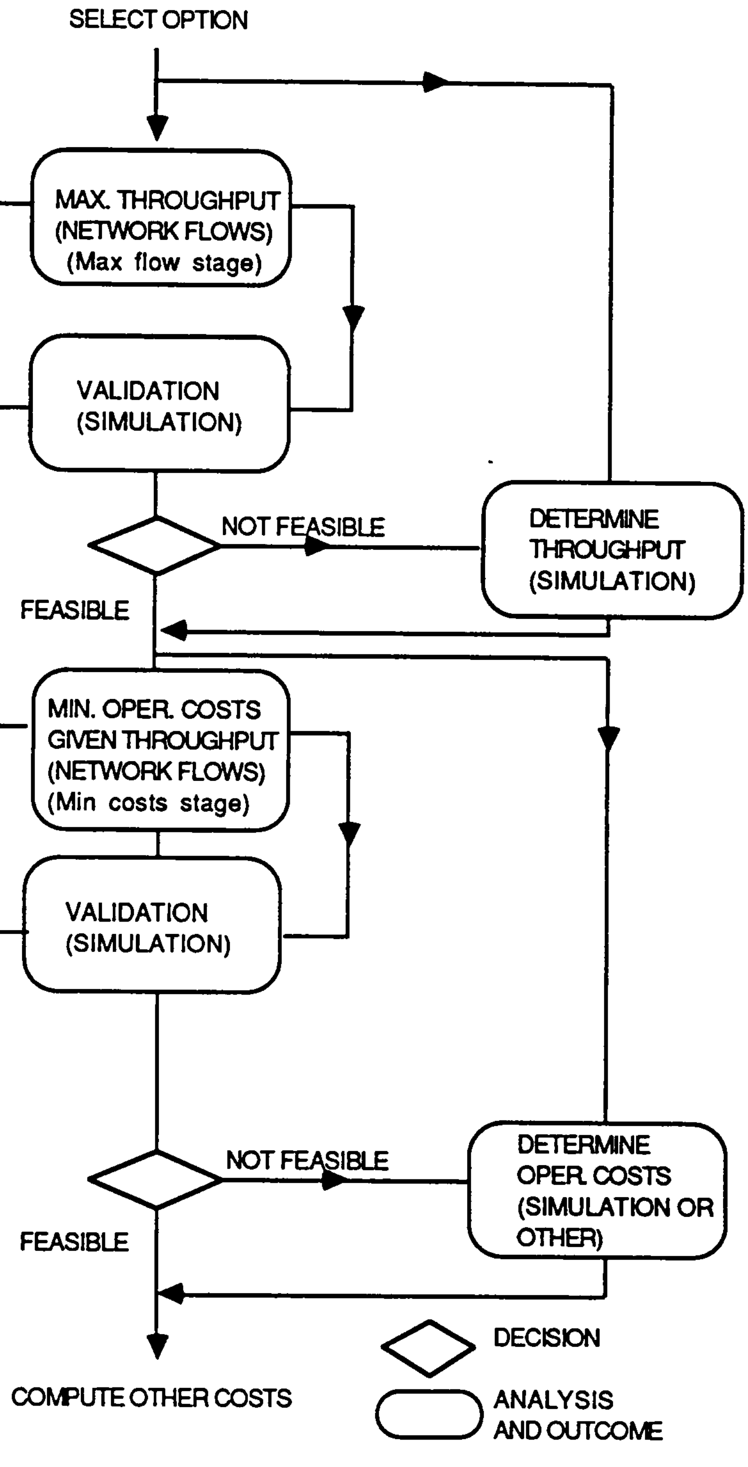


FIGURE 24.OPERATIONAL ANALYSYS SUBFRAMEWORK

feasible). Simulation is used in conjunction with network flows mainly to validate analytical solutions in terms of their operational feasibility. Analytical models are used since they can explore a large number of alternatives that could not be explored quickly with simulation.

As was said earlier, the decision maker has the choice of using simulation or both simulation and analytical techniques when selecting an alternative. The main role of analytical techniques is that of restraining the solution domain quickly, so that solutions can be refined at the detailed design stage. Moreover, analytical solutions provide an ideal system that guide the simulation process. For example, the computed optimal fleet size is invariably lower when static models are used than when compared with the number determined with simulation. This is due to dynamic scheduling aspects such as dispatching rules (which produces delays) not captured in static models (Egbelu, 1987). The role of simulation, in this particular case, would be to devise efficient dispatching rules that make the system closer to the ideal (static) case.

In other words, analytical techniques and simulation should interact with one another. Analytical techniques drive the simulation to come up with a detailed solution that is close to the ideal system. Simultaneously, simulation drives analytical techniques to have models that reasonably reflect reality (for example, by including proper parameters that are proxies for dynamic aspects captured with simulation).

If an analytical model is used in order to find the increase in throughput, then some assumptions are likely to be made about dynamic aspects of the system. The (optimal) solution obtained at this point should be tested with a simulation model to insure feasibility from a dynamic standpoint. Simulation results will test those assumptions made at the analytical stage. If simulation results in terms of throughput differ markedly from the analytical solutions, then the decision maker should backtrack to the analytical stage and revise his assumptions about the system and reoptimize. If there is no convergence between the analytical and the simulation results, then the decision maker should resort to the use of a feasible solution using simulation and go on from there to the next step in the decision process.

If the system has been successfully optimized from an operational standpoint, then the decision maker can look at operational costs themselves. Again, analytical techniques can be used in conjunction with simulation. At the previous stage, a flow pattern was sought that would maximize the overall throughput. Here, given that throughput, an attempt is made to minimize operational costs by rearranging the flows within the FMS (details of the linear program will be given in the next section). Simulation is then used, as in the previous stage of the process, to verify the analytical results. If no convergence occurs between the optimal solution and simulation results, then operational costs must be approximated with some other heuristic procedure.

VII- 5. MODELING FMS/AGVS WITH NETWORKS

When using analytical models such as network flows pertaining to AGVS, a fundamental objective is to minimize the load (in vehicle-hours) on the AGVS. By doing so, not only are operational costs likely to be minimized, but also the cost of the AGVs themselves, as fleet size is minimized as well by this procedure. Another objective is throughput maximization which consists essentially of maximizing flows distributed within the network.

One of the models suggested in both the first (flow maximization) and second (cost minimization) stages is a variation of the linear program developed by Leung and Tanchoco (1987). This model attempts to maximize profits of an FMS/AGVS within a multiple machine replacement framework. Two types of costs are taken into account in an integrative manner: machining and transportation costs, both directly related to the flow of parts between machines. The throughput of each part type is given. Machine and AGVS capacity are also given with the maximum amount of resources (energy, maintenance,...) available. This model essentially allocates flows to segments linking machines.

The second model (Leung, et al, 1987; Maxwell and Muckstadt, 1987), is an assignment program. The flows between machines are given, and the objective is to minimize AGVS system load while assigning vehicles to these flows. The Maxwell and Muckstadt model minimizes empty vehicle time, given the flow of loaded vehicles. The Leung model minimizes both loaded and empty vehicle-time and takes into account the possibility of using more than one fleet of AGVs in the same layout. Each of these fleets is characterized by a vehicle speed and vehicle capacity (in terms of weight). Here, capacity will be defined in terms of the maximum number of parts that can be loaded on the vehicle. However, when using this framework, the flows of parts must be assumed at the outset and are considered parameters in the program. Therefore, if a change in total AGVS capacity occurs due to an increase in fleet size or vehicle speed, the corresponding increase in flows must be estimated, which makes this model troublesome to use (within a framework that studies changes of throughput coming from modifications of the system).

In the next section, the integration of the Leung and Tanchoco model within the overall decision framework will be described. This model will be used mainly to maximize the flow within the FMS and to minimize operational costs of this flow, given overall throughput requirements.

VII- 5.1 Flow Maximization Stage

By using the notation found in Leung and Tanchoco, the objective function that maximizes the overall throughput processed by the system is,

$$\text{Max} \quad \sum_{p} Q_p \ ,$$

where Q_p is the throughput of part type p processed by the FMS. The constraints are the following:

Product mix constraints:

$$Q_p = \beta_p Q_{p+1} \quad , \qquad \text{for all p.}$$

This set of equations restrain the flow of parts in a way to restrict the relative proportion of a part type to another in accordance to the overall product mix. If for example, the demand of part type one is twice that of part type two, and it is decided the system would produce these parts in this proportion, then β_1 would be set equal to 2/3 . If product mix is not a constraint, then the above equations may be dropped.

In order to clarify subsequent developments, the following decision variable is defined (Leung and Tanchoco, 1987) :

Y_{pkms} : the flow amount of part type p which flows from the sth machine to the mth machine for the kth operation.

This variable is necessary in order to track the flow of materials that goes from one machine to another. This variable is also useful for taking into account the flexibility of machines themselves which can process more than one part type. At each operation step a decision has to be made as to where to send the flow of parts. More than one machine can process the part at a certain operation step, and therefore it may be advantageous to split that flow and send it to several machines (for that particular job step).

Flow distribution constraints:

$$Q_p - \sum_{m} Y_{p1m0} = 0 , \qquad \text{for all p,}$$

where Y_{p1m0} is the flow amount of part type p that goes to machine m from the loading/unloading station (machine 0) for the first operation. These constraints link the throughput Q_p to what goes on in the FMS in terms of the flows that enter the network.

The next set of constraints pertain to flow equilibrium and inputs allocation (Leung and Tanchoco, 1987):

Logical constraints:

$$\sum_{s} Y_{pkms} = \sum_{r} Y_{pkrm} \ , \quad \text{for all p and k}$$

These constraints are simply flow equilibrium conditions at each machine . The number of parts that goes to a machine should be equal to the number leaving it.

<u>Allocation constraints- upper limits on input amount</u>:

$$\sum_{p} \sum_{k} \sum_{m} \sum_{s} u_{lm} t_{pkm} Y_{pkms} \leq U_l, \quad l = 1, 2, 3 \ldots L$$

where u_{lm} are the inputs required by machine m per unit time; t_{pkm} is the processing time required by the kth operation of part p on machine m; U_l is the amount available of the lth input resource.

<u>Allocation constraints- machine capacity</u>:

$$\sum_{p} \sum_{k} \sum_{s} t_{pkm} Y_{pkms} \leq T_m, \quad \text{for all m},$$

where T_m is the capacity (in time units) of machine m.

<u>Allocation constraints- AGVS capacity</u>:

$$\sum_{p} \sum_{k} \sum_{m} \sum_{s} (1/\alpha)\, d_{ms} Y_{pkms} \leq D \quad ,$$

where d_{ms} is the distance traveled form the sth machine to the mth machine, and α is the average utilization rate of the AGVS. This last parameter takes into account the empty travel time of the vehicle(s) and increases the load on the MHS system accordingly.

This parameter must be estimated. Finally, D is the capacity of the AGVS (in vehicle-distance).

VIII- 5.2 Cost Minimization Stage

The next model formulation attempts to minimize costs, given the throughput Qp found in the last program. The objective function in this case is (Leung and Tanchoco, 1987):

Min (Machining Costs) + (Transportation costs)

The machining costs are,

$$\sum_{p}\sum_{k}\sum_{m}\sum_{s} C_m t_{pkm} Y_{pkms}$$

where C_m is the processing cost per unit time on machine m and,

$$C_m = \sum_{l} g_l u_{lm} \quad ,$$

and where g_l are the input costs, and u_{lm} are the inputs required by machine m.

The transportation costs are:

$$\sum_{p}\sum_{k}\sum_{m}\sum_{s} w(1/\alpha) d_{ms} Y_{pkms}$$

where w is cost per unit distance traveled and d_{ms} is distance traveled from the sth machine to the mth machine.

Throughput constraints:

$$\sum_{m} Y_{p1m0} = Q_p \qquad \text{for all } p$$

This set of constraints makes sure that the FMS processes the amount Q_p. The remaining constraints are the same, namely, logical and allocation constraints.

VII-6. MODEL LIMITATIONS

When using simulation, all these constraints are taken care of implicitly, as well as dynamic considerations such as vehicle blocking, dispatching rules and control logic. With analytical techniques, these aspects of FMS/AGVS are either working hypotheses or simply not taken into consideration. For example, the coefficient α (utilization of individual AGVS) used in the Leung and Tanchoco model, and which is related to empty travel, must be assumed or estimated in some way. The utilization of AGVS can be determined with simulation. But in order to do this, the flows of materials must be known as well. This is why in this particular case, simulation and network flows must be used in an interactive way, so that their results can be mutually supportive.

The main limitation of the above model is that the fleet size has been assumed to be one. For fleet sizes higher than one, the use of the coefficient α becomes more problematic. Recall that this parameter is the proportion of time the vehicle is being used for actual transport. When included in the model, it has the effect of reducing the total capacity of the AGVS (in terms of vehicle-second or vehicle-foot). The amount of time vehicles spend traveling empty to get loads can be quite significant and has a tendency to increase as more vehicles are added to the system (even though the overall throughput goes up). The utilization rate become more difficult to assess without simulation.

Other aspects which need to be included in the utilization rate α is time lost due to loading and unloading activities which represent lost capacity. Vehicle idle time (due to the inefficiency of the overall FMS to dispatch and assign jobs more quickly) is another factor that reduces AGV utilization. Finally, blocking should also be taken into account, when it appears to significantly reduce AGV capacity due to congestion and network limitation.

Another limitation of models such as network flows is their deterministic bias. Flows determined by the program must be considered as average figures in the face of uncertainties such as time of arrival of parts in the system and their routing. Only simulation will confirm if these flows, which represent aggregate number of parts going from machine to machine, are realistic. Finally, the model becomes an approximation of reality when more than one type of vehicle is used. In this case, the flows between machines include some entities which are in fact batches of two loads, if the capacity of some vehicles is twice that of others.

Another type of limitation has to do with the two stage approach included in the operational analysis. This framework assumes that simulation time is available for both flow maximization and costs minimization. Simulation is typically time consuming and the analysis of the FMS may be curtailed due to time and computing costs constraints. Moreover, the benefits from performing the second stage may be marginal as the maximization of flows within the network is likely to yield an optimal solution that also minimizes operational costs. This would the case if these costs were essentially transportation costs since the flow within the network is likely to be maximized when distance traveled between nodes are minimized. The second stage is likely to be useful when machining costs are also included in the analysis. In this case if might be advantageous to modify the solution obtained in the first stage so that some of the flow may be diverted to a machine whose processing costs is lower.

VII- 7. A VEHICLE ASSIGNMENT MODEL

An alternative to the Leung and Tanchoco model are models that assign vehicles to flows already determined (Leung, et al, 1987; Maxwell and Muckstadt, 1987). The result of such linear programs is a vehicle assignment by type to each segment linking machines that minimizes overall AGVS system load. As was said earlier, the main problem with this approach is the flow of parts must be known, and therefore is fixed instead of being a variable. This model can be used, however, in the second stage of the operational analysis by including transportation cost parameters.

The model could be used in conjunction with simulation, but the interfacing with simulation is likely to be more complex than when using the Leung and Tanchoco model. In that model, only optimal flows between machines were specified. Here, not only are those flows specified, but vehicle type per segments are specified as well. Therefore, a simulation program would have to take into account these constraints.

The following variables are to be used (Leung, et al, 1987),

x_{ijk}, is equal to 1 if the kth vehicle is to travel form station i to j; 0 otherwise

z_{ijk}, number of empty trips of the kth vehicle from station i to j

v_{ij}, flow of parts between machines i and j

L_i, loading time per unit load

U_i, unloading time per unit load

t_{ijk}, time required by the kth vehicle to go from station i to j.

w, weight of each part

y_k, weight capacity of vehicle type k

$[\ ]^-$ is the next lower integer

$[\ ]^+$ is the next higher integer

In the Leung, et al, formulation, the objective function is:

Min (Loaded travel) + (Empty travel)

where load in vehicle-time is

$$\sum_i\sum_j\sum_k (L_i + U_j + t_{ijk})[v_{ij}/[y_k/w]^-]^+ x_{ijk} \text{ , and}$$

empty load in vehicle-time is

$$\sum_i\sum_j\sum_k (t_{ijk}) z_{ijk} .$$

At this point, operational cost parameters associated with vehicle travel could be included. For instance, c_{ijk} would be the unit cost of travel for the kth vehicle going from station i to station j.

The constraints of this program are,

<u>One vehicle per transfer of part</u>:

$$\sum_k x_{ijk} = 1 \text{ if } v_{ij} > 0,$$

$$= 0 \text{ if } v_{ij} = 0$$

This constraint assumes that only one vehicle will be used to transfer all parts between stations i and j.

<u>Flow equilibrium (for vehicles)</u>:

$$\sum_{\substack{j \\ j \neq i}} z_{jik} - N_k(i) \geq o \text{ for all } i, k$$

$$\sum_{\substack{j \\ j \neq i}} z_{ijk} - N_k(i) \geq 0 \text{ for all } i, k$$

where

$$N_k(i) = \sum_j [v_{ij}/[y_k/w]^-]^+ x_{ijk} - \sum_j [v_{ji}/[y_k/w]^-]^+ x_{jik}$$

for all k.

<u>Vehicle capacity</u>:

$$\sum_i \sum_j (L_i + U_j + t_{ijk})[v_{ij}/[y_k/w]^-]^+ x_{ijk} + \sum_i \sum_j (t_{ijk}) z_{ijk} \leq C_k$$

for all k.

C_k is the capacity of vehicle k and is equal to the available time C_k' multiplied by α_k (the fraction of time the vehicle is non-idle).

VII-8. INTEREST RATE AND MULTI PERIOD INVESTMENT PLANS

So far, no mention of interest rates or time value of money has been made in this evaluation process. If the investment plan covers only a few years, then the discounting factor is likely to have little effect. However, if it is forecast that several years will be needed in order to realize the overall investment plan, then the interest may have an effect on the individual cash flows occurring at each period. If the objective is to minimize overall cost over the years covering the investment project, then the discounting factor is likely to have a delaying effect on investing during early periods as future costs have less and less weight. On the other hand, given a discount factor, the high future costs (including opportunity costs) may favor early investment decisions (since these costs have relatively more weight than others occurring earlier). In effect , those opportunity costs (which will occur if no investment is done early) may be large enough to offset the impact of interest rates, and thus justify investment at early stages of the overall plan .

Therefore, a multi-period planning horizon involves a minimization procedure of first (F), operations (Op.), current change (CC) and opportunity costs (Opp.) through time:

$$\text{Min} \quad \sum_t (F.\text{costs})_t + (Op.\text{costs})_t + (C.C.\text{costs})_t + (Opp.\text{costs})_t$$

where t is the time at which the decision is made. At each time t there is likely to be several combinations of these costs. The problem is thus to determine the optimal pattern of investment through the overall planning horizon.

The above analysis is likely to be useful for strategic planning as the rate at which these new manufacturing technologies are introduced in the organization is an issue. As it was said earlier, a budget constraint can limit the amount of changes permitted for a given period. These changes can also be limited by the capability of the organization to absorb new technologies (due to learning curves and training).

VII-9. SUMMARY

Decision frameworks were designed according to the objectives of this research. Frameworks developed involved the interdisciplinary aspects of the evaluation and included opportunity costs as well as other conventional costs. A great deal of attention was given to operational costs which are likely to be linked to economies of scope. It was said that this particular aspect of FMS did not directly concern material handling systems, as these economies of scope were originating from the flexibility of machines. However, a material handling system such as an AGVS is likely to exploit those flexibilities and therefore contribute indirectly to these economies of scope. The sub-framework pertaining to these operational costs involved existing network models and the use of simulation. The network models were used for optimizing purposes and simulation for validating the optimal solution. This part of the evaluation process recognizes the limitations of analytical models. If those limitations are excessive, then only simulation should be used. If these limitations appear not to hinder the validity of the models, then optimization should be used. The optimization process was used for optimizing the flow within the network as a first step and to minimize costs of this overall flow. Finally , it was shown how this framework could be extended to a multi period investment plan for new manufacturing technologies.

VIII - FMS/AGVS ANALYSIS WITH SIMULATION

In this part of the dissertation, it is shown how simulation can be used within the operational analysis framework as described in Figure 24. It also demonstrates the use of the flexibility indices for analyzing FMS/AGVS.

In this chapter, results of simulation tests are described for two models: the first model called the base model is an FMS without input and output buffers (except at the loading/unloading station) and another one with buffers at each machine or cell . Three basic layouts are examined: a single loop layout, a ladder layout and an intermediate alternative between these two *extreme* cases. The AGVS is essentially a taxi system that transports and unloads parts on machines. Implications in terms of flexibility of these two systems are discussed.

VIII-1. DESCRIPTION OF THE BASELINE MODEL

The experiments in this research have been designed to study the behavior of an FMS/AGVS when the material handling system is the bottleneck. What follows, therefore assumes that the cells or machines have the capability of satisfying the demand perceived by the firm. The alternative models have been simulated with the material handling extension of SLAM-II (MHEX).

The models used in this research are illustrated in Figures 25, 26 and 27 with variations of the same FMS in terms of layout configurations. Three types of layouts are considered: a single loop layout with six machines on the loop (1*6), a double loop layout with three machines on each loop (2*3), and a six loop layout with one machine on each loop (6*1). The system processes two types of job : one whose routing sequence is machines 1, 2 and 3, and the other, 4,5 and 6. Product mix is assumed to be 50% for job type one and 50% for job type two. Arrivals of these jobs into the system are assumed to follow an exponential distribution and at their arrival, they have an equal probability of being of either type. In order to make the overall analysis more manageable, processing times for each machine are assumed to be deterministic and of equal duration.

The processing of jobs is as follows. A load enters the system by waiting in line for a fixturing station. The fixturing station has a capacity of one for low demands and is set at three for high demands. In other words, the station can handle up to three loads simultaneously. This insures that this part of the system never becomes a bottleneck. When the fixturing station is available, a fixture is fitted on the part to be processed . Then, the part takes a space at an output buffer station (if there is one available) and waits until it moves up front in the queue in order to request the first machine according to its routing sequence. When the particular machine is available it is "seized" by the part. At this point, the load requests a vehicle. In order to avoid shop locking phenomena, the model has been designed so that a load never requests a vehicle before a machine is available. When a vehicle is idle and when there are no jobs in the system with higher priority, it is dispatched at the control point associated with the position of the fixturing output buffer within the layout. A part already in the manufacturing system requesting a machine will

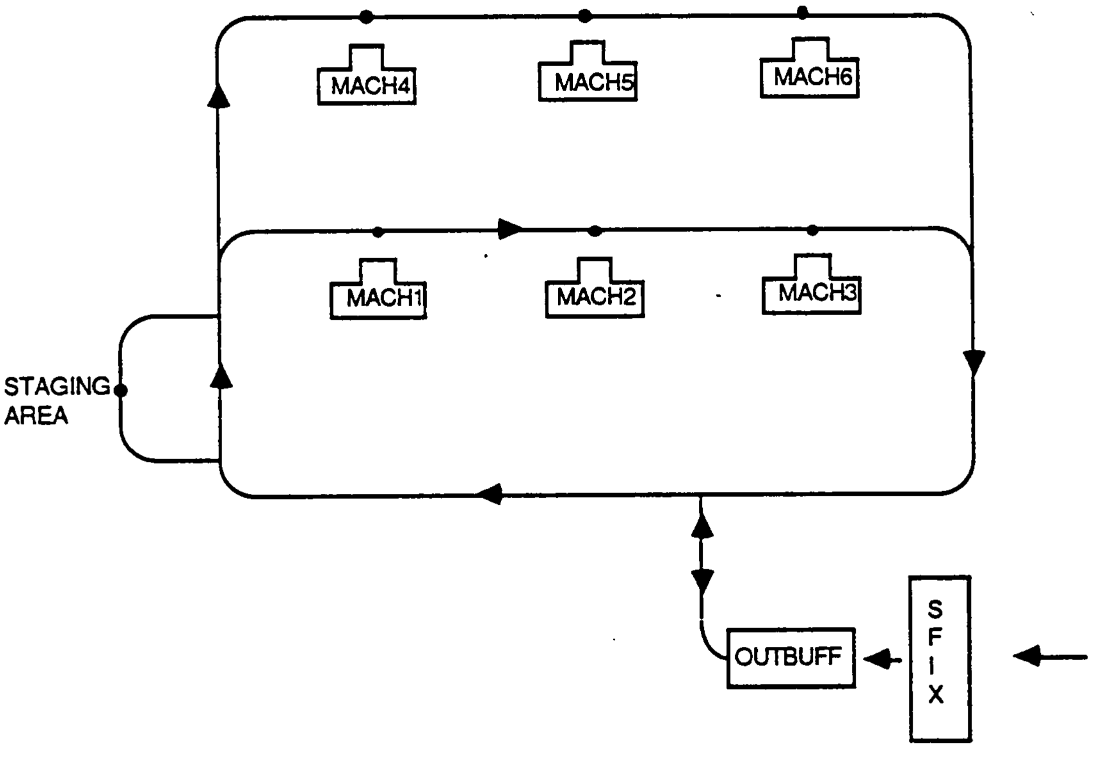


FIGURE 25. FMS/AGVS UNIDIRECTIONAL (2*3) , (PRITSKER, 1986)

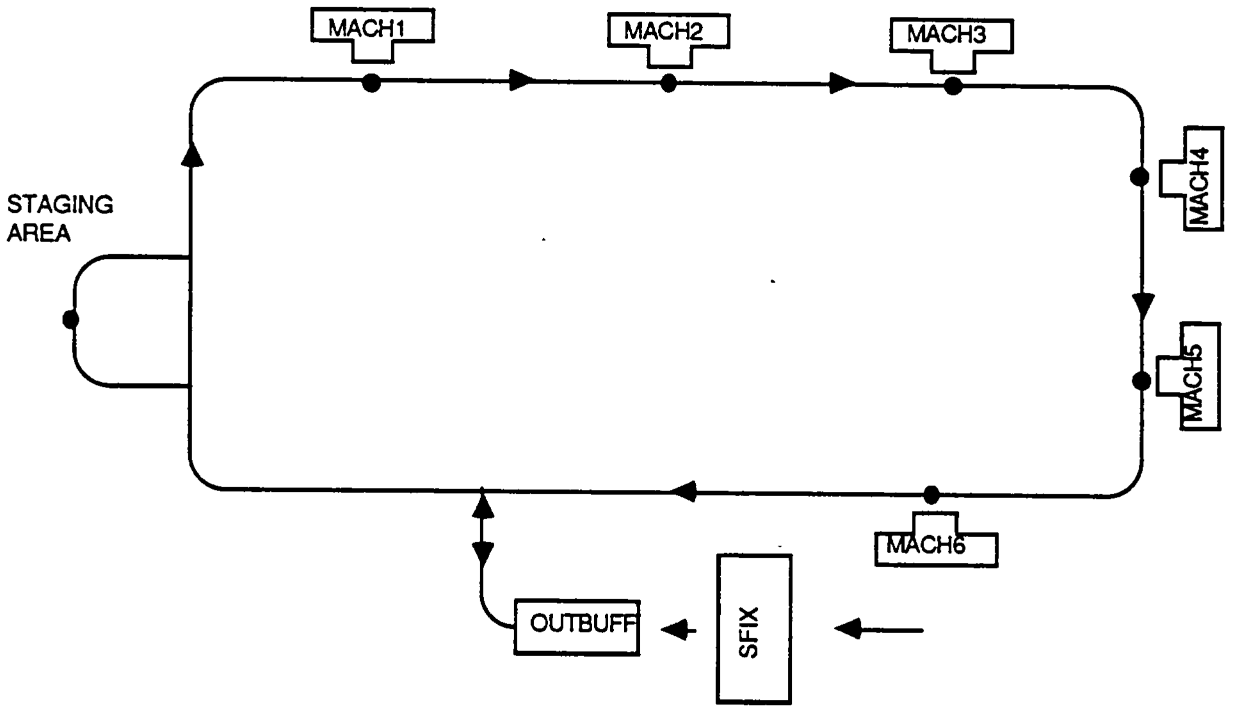


FIGURE 26. FMS/AGVS 1*6, UNIDIRECTIONAL SINGLE LOOP LAYOUT

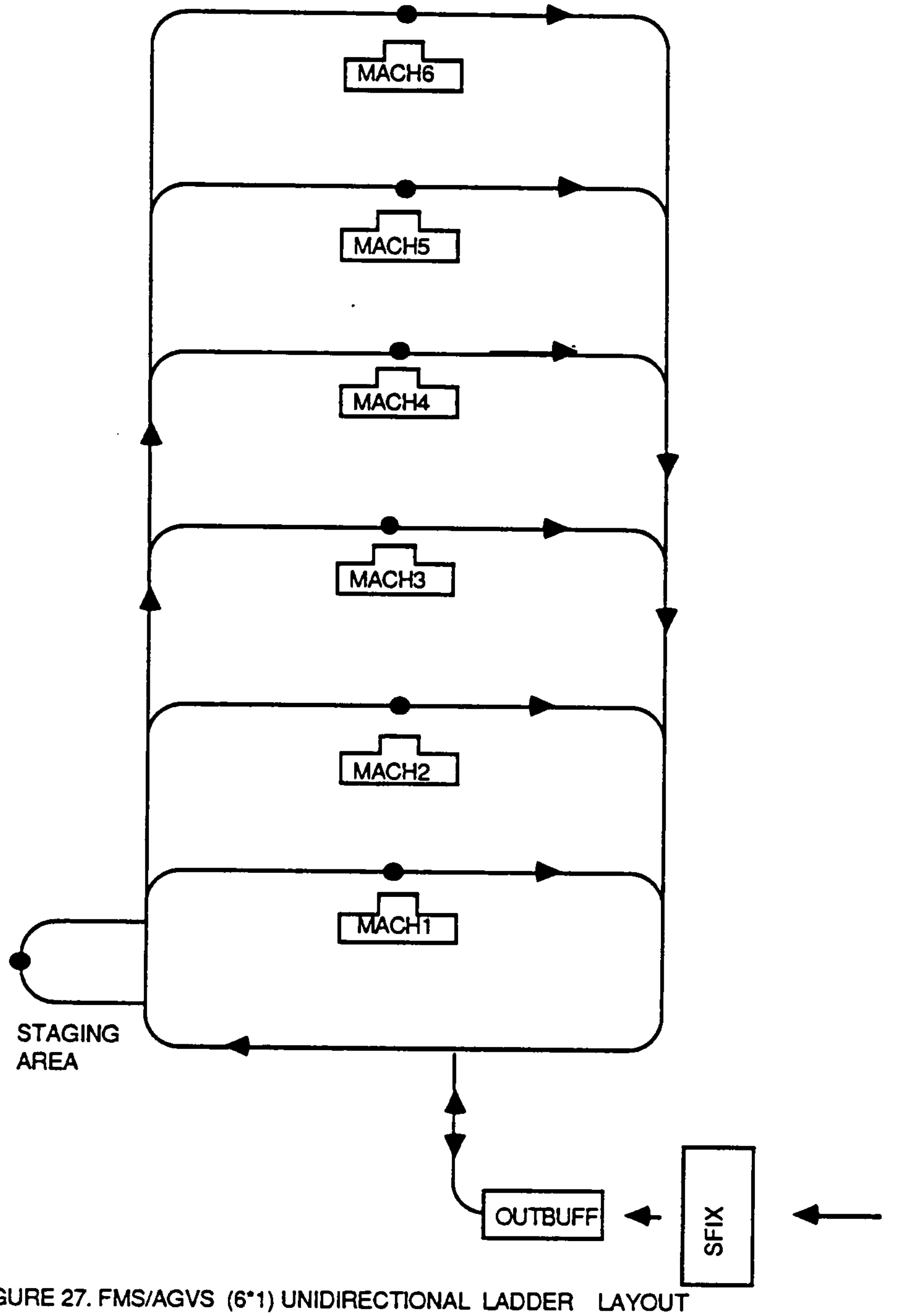


FIGURE 27. FMS/AGVS (6*1) UNIDIRECTIONAL LADDER LAYOUT

have priority over another part (requesting that same machine) at the fixturing station. In other words, no machine will be allocated to a requesting load, if there is another load in the system already waiting for it. This procedure insures that all parts are being evacuated as soon as possible from the system (and also to avoid possible shop locking in the case of intertwined routings with overlapping machine sequence).

When an AGV arrives at the control point (associated with the fixturing station) the part is loaded on the vehicle and is routed to the machine. At that point, it is unloaded and processed by the machine (there is no input or output buffers associated with machines). When the part is processed, the next machine is requested. Then, another vehicle is requested again. The part stays at the current machine location until the vehicle arrives to pick it up. The vehicle transports the part to the next machine according to the routing sequence.

This process is repeated until the part has been processed by the last machine, then, it is routed back to the fixturing station. At this point, the fixture is removed from the part, and then exits the system.

Some considerations are worth noting concerning the AGV fleet, layout configuration and control procedures. The AGV system is constituted of a uniform fleet of vehicles with a predetermined fleet size, empty vehicle speed, loaded vehicle speed, vehicle length, buffer distance, and idle and vehicle initiated dispatching rules. When a vehicle is idle, it is routed to a staging area. In this model, the vehicle initiated dispatching rule is FIFO: as job requests occur within the system, they are ordered in a first in first out fashion.

Segment lengths, capacity and directionality are specified as well as contention rules and routing rules associated with control points. Each segment is defined by two control points. To each of these control points are associated a contention and routing rule. In this model, the shortest distance rule is used for all control points. When a vehicle arrives at a control point it evaluates the remaining distance to be covered. In the case of blocking, a re-evaluation of that distance is done. So far only unidirectional segments are assumed in Figures 25 ,26 and 27. In the case of bi-directional segments, a contention rule must be specified correctly. Three options are immediately . possible here: FIFO, a rule based on the closeness of the destination and a rule based on a load status priority scheme. The later scheme is the following: 1. " ...A vehicle with only one possible exit will cause the direction of lower priority vehicles to reverse. 2. A vehicle traveling full to unload will cause the direction of a lower priority vehicle to reverse. 3. A vehicle traveling empty to load will cause the direction of idle vehicles to reverse " (Pritsker,1986). This last priority scheme is the one used in the simulation tests. In particular, it will be active for control points joining bi-directional segments, while the FIFO rule is for all other unidirectional ones. Finally, an additional consideration about vehicle request: the work center or (machine) initiated dispatching rule is specified as FIFO, which selects the vehicle that has been idle for the longest time.

All files (or queues) used in the simulation model follow the FIFO discipline, except the file associated with the fixturing station whose ordering rule of loads is based on their arrival time in the system. This is another procedure that minimizes chances of shop locking as parts exit as fast as possible from the system when they are fully processed by machines.

Each run starts with an empty production system and lasts about 55 hours (200000 seconds). One test is comprised of three runs each having different seeds in order to take into account variability due to the randomness of interarrival time. However, it appears that throughput (the main performance measure in this research) does not vary much (less then 10% in most cases), as machine processing times are deterministic.

VIII-2. PRELIMINARY RESULTS

Table 2 shows some preliminary tests using the double loop layout configuration (Figure 25). As demand increases, the AGV system becomes the bottleneck when the fleet size is one. However, when the fleet size is increased by one, throughput does not lag behind demand. Table 3 and Figure 28 show the behavior of throughput as a function of fleet size when demand is set to 333 units. Several statistics are shown to illustrate the optimal vehicle fleet size for which throughput is maximized (or in this particular case the minimum number of vehicles that satisfies demand). Average waiting times of the parts are given for each fleet size. A blocking statistic is also included and is measured by the proportion of vehicle-seconds that the AGV fleet experiences blocking. As fleet size is increased to five, excessive blocking occurs and throughput goes down.

VIII-3. THE UNIDIRECTIONAL CASE

The three main layout configurations (single loop, double loop and the six loop system) were tested. Results are shown in Table 4

TABLE 2. PRELIMINARY RESULTS (LOW INTENSITY DEMAND)

DEMAND	181	200	222	250	285	333	400	421	444
THROUGHPUT (1 AGV)	178	194	213	228	236	239	239	238	238
THROUGHPUT (2 AGV)	179	195	218	241	277	326	395	414	438

TABLE 3. THROUGHPUT AS A FUNCTION OF FLEET SIZE

FLEET SIZE	Throughput	Waiting (1)	Waiting (2)	Waiting (3)	Waiting (4)	Waiting (5)	Blocking(6)
1 AGV	239	13351	410	510	445	556	0
2 AGVs	326	136	24	101	74	91	0.0283
3 AGVs	327	148	1	99	39	51	0.0387
4 AGVs	326	146	0	99	37	30	0.0383
5 AGVs	101	38487	0	1521	39	73	0.75

(1) Waiting to get in the system (seconds)
(2) Waiting for a vehicle to be dispatched
(3) Waiting for a vehicle to come to control point associated to fixture station
(4) Waiting for a vehicle to come to control point within the system
(5) Waiting for a vehicle to come to control point in order to get to the fixturing station and leave the system
(6) Proportion of blocked vehicle -seconds

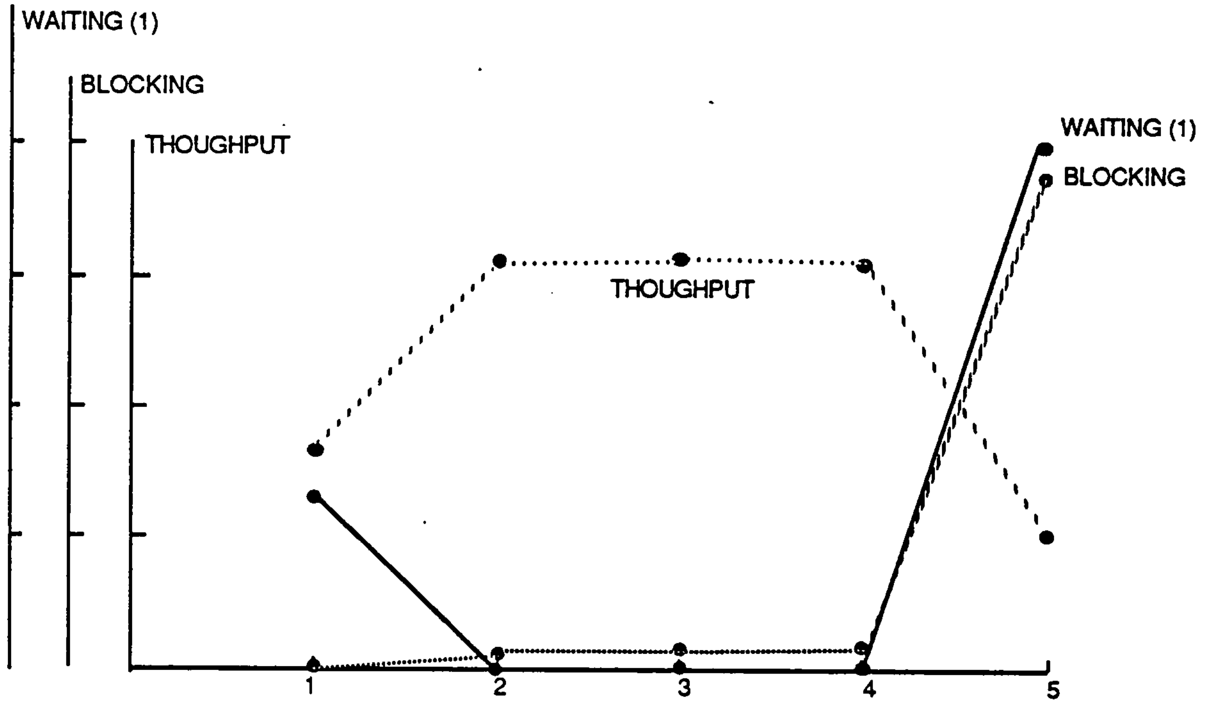


FIGURE 28. THROUGHPUT, BLOCKING, AND WAITING TIME TO ENTER SYSTEM AS A FUNCTION OF FLEET SIZE

and illustrated in Figures 29, 30 and 31. It appears that the single loop configuration is quite resilient to variation in fleet size: no blocking occurs for fleet size ranging from two to four. At five, throughput decreases. As routing is changed and perturbed, throughput tends to go down with the exception of the six loop layout which, while poor in terms of volume flexibility as far as fleet size is concerned, is stable under such changes.

As one goes from the single loop layout to the double loop and to the six loop layout, the system becomes less able to use fleet size in order to increase throughput, and other means such as an increase in speed is necessary. This seems to be caused by larger distances between machines as the number of loops and rungs are added to the layout. The high routing flexibility found in the six loop layout presumably comes from the fact that each machine is located on a rung, thereby minimizing congestion. However, the single loop layout does show some routing flexibility (depending on how it is defined). By inspection of Figure 29, it can be seen that the system can respond to changes in routing up to a certain point by adding vehicles. This illustrates the problem of interdependencies between flexibilities, as a counter action (namely increasing fleet size) that is typically used in volume flexibility can also be used in routing flexibility.

Finally, the in-line layout (Figure 32) appears inefficient as it fails to respond to the same conditions imposed on the previous systems. Simulation runs not shown here indicate that excessive blocking occurs and this system locks fairly easily for fleet sizes over two. It appears that this particular layout is acceptable for only relatively light demands.

TABLE 4 RELATIONSHIPS BETWEEN THROUGHPUT, FLEET SIZE, ROUTING AND VARIATIONS IN UNIDIRECTIONAL LAYOUTS

Layout	1 * 6					2 * 3					6 * 1				
Fleet size	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Routing 1- 1,2,3 2- 4,5,6	323	515	565	590	410	240	466	594	613	502	199	389	533	567	X
Routing 1- 3,2,1 2- 4,5,6	269	477	562	594	589	207	422	554	587	x	198	389	525	571	X
Routing 1- 3,2,1 2- 6,5,4	234	431	541	576	544	178	373	472	561	436	198	389	525	571	x

X: BLOCKING DUE TO INSUFFICIENT FLEET SIZE OR DUE TO TRAFFIC CONGESTION

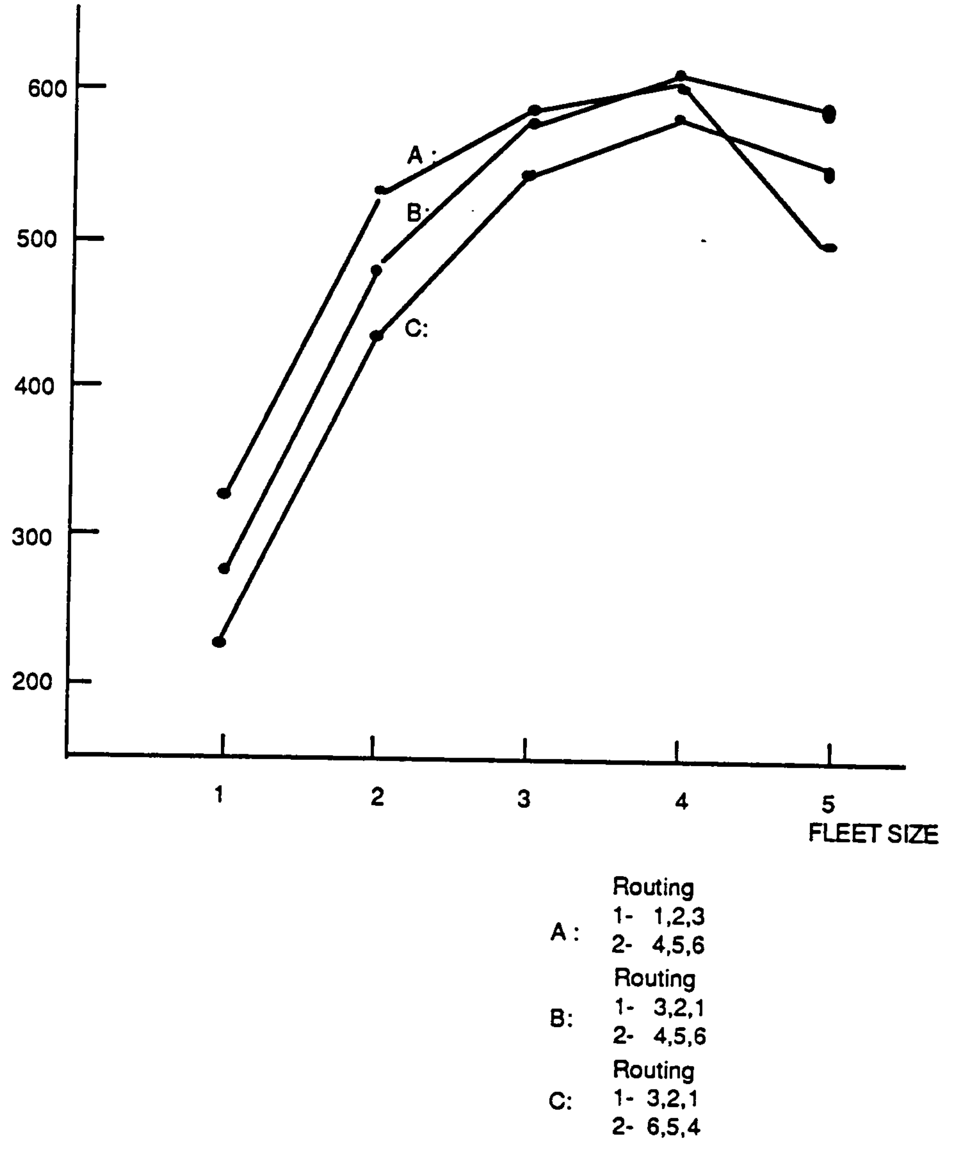


FIGURE 29. RELATIONSHIPS BETWEEN THROUGHPUT , FLEET SIZE, ROUTING IN UNIDIRECTIONAL LAYOUT 1*6

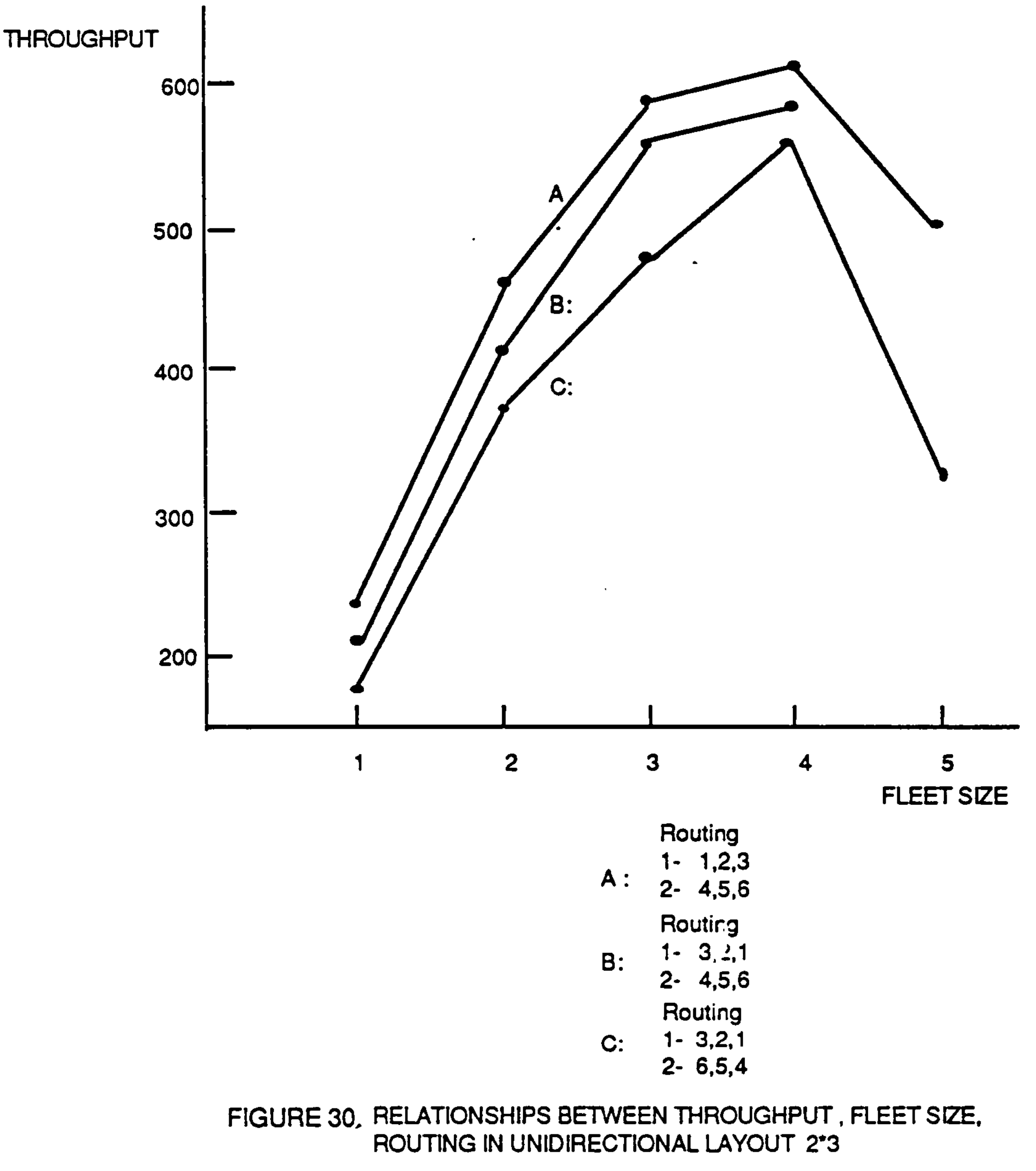
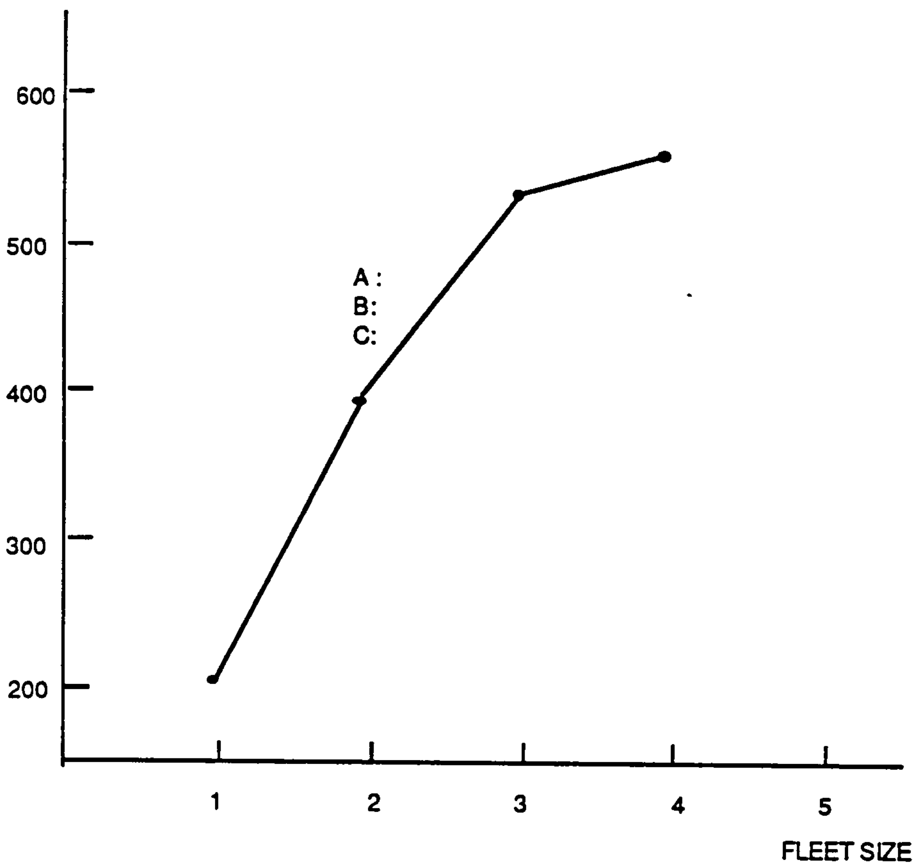


FIGURE 30. RELATIONSHIPS BETWEEN THROUGHPUT, FLEET SIZE, ROUTING IN UNIDIRECTIONAL LAYOUT 2*3



A : Routing
1- 1,2,3
2- 4,5,6

B: Routing
1- 3,2,1
2- 4,5,6

C: Routing
1- 3,2,1
2- 6,5,4

FIGURE 31.RELATIONSHIPS BETWEEN THROUGHPUT , FLEET SIZE, ROUTING IN UNIDIRECTIONAL LAYOUT 6*1

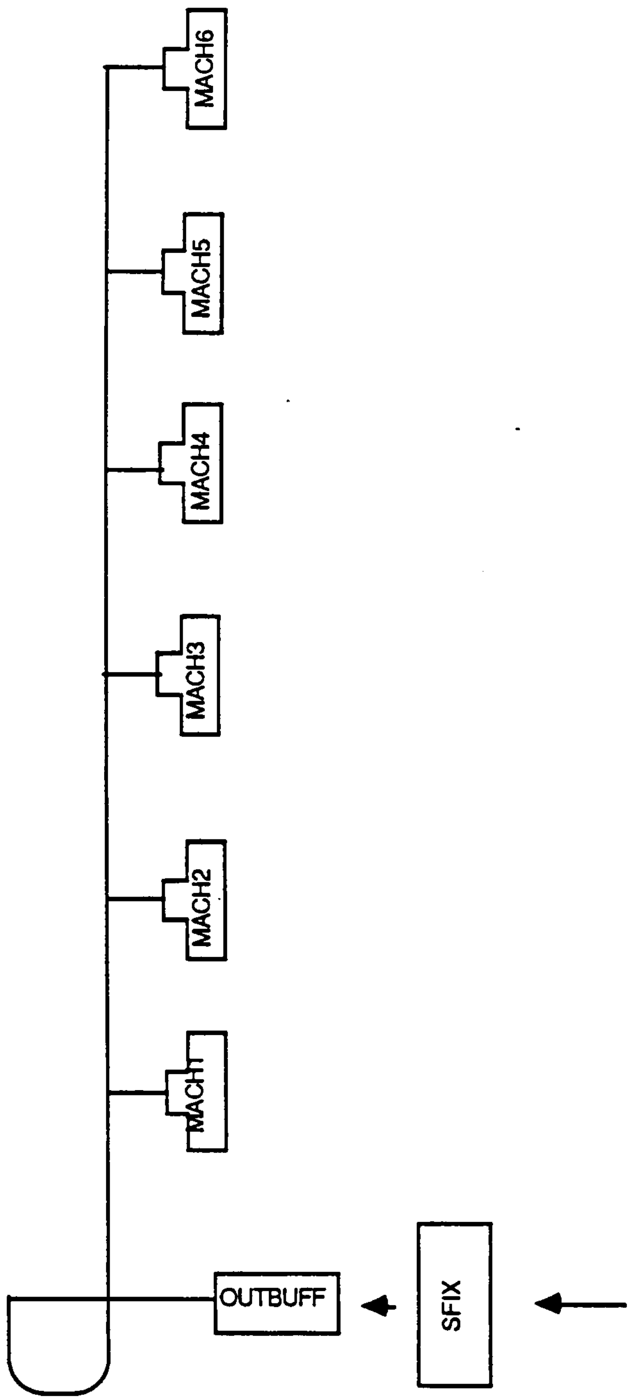


FIGURE 32. FMS/AGVS IN LINE LAYOUT

VIII-4. THE UNI/BI-DIRECTIONAL CASE

Modifying the layout by changing segments from being uni-directional to bi-directional makes the system more complex (because of contention rules), but should reduce the required fleet size. Figures 33, 34 and 35 show the same layout configurations, but with segments linking machines that are now bi-directional. The only system that functions under such a design is the six loop layout when throughput nearly reaches system capacity (Table 5). However, such a system is sensitive to routing changes, as the disposition of machines makes it easier for routing C and does not produce significant improvement on A. It can be seen in Figure 36 that volume flexibility has been increased for the C routing, and, to a lesser extent, for the B routing. The effect of bi-directionality is difficult to assess, as it improves performance in very specific cases, but does not work at all for other systems that were otherwise performing well in terms of volume flexibility.

VIII-5. VOLUME FLEXIBILITY: (ΔTH/TH)/(ΔFT/FT)

The preceding results indicate the following points. Layouts such as the one in Figure 27 involving several branching points between machines are not necessarily superior, in terms of routing flexibility as defined in this research, to single loop layouts where machines are located on the same track. The results show that this particular configuration works relatively well when vehicle speed is relatively low and blocking is not a factor. Vehicle speed was set to 3.0 ft/sec when loaded and 3.5 ft/sec when unloaded. Such

TABLE 5. RELATIONSHIPS BETWEEN THROUGHPUT, FLEET SIZE, ROUTING AND VARIATIONS IN BIDIRECTIONAL LAYOUTS

Layout	1 * 6				2 * 3				6 * 1					
Fleet size	2	3	4	5	2	3	4	5	1	2	3	4	5	6
Routing 1- 1,2,3 2- 4,5,6	X	X	590	X	514	600	X	X	215	400	531	576	X	X
Routing 1- 3,2,1 2- 4,5,6	-	-	-	-	-	-	-	-	226	426	552	588	592	X
Routing 1- 3,2,1 2- 6,5,4	X	X	X	X	X	544	581	X	260	478	618	627	627	X

X: BLOCKING DUE TO INSUFFICIENT FLEET SIZE OR DUE TO TRAFFIC CONGESTION

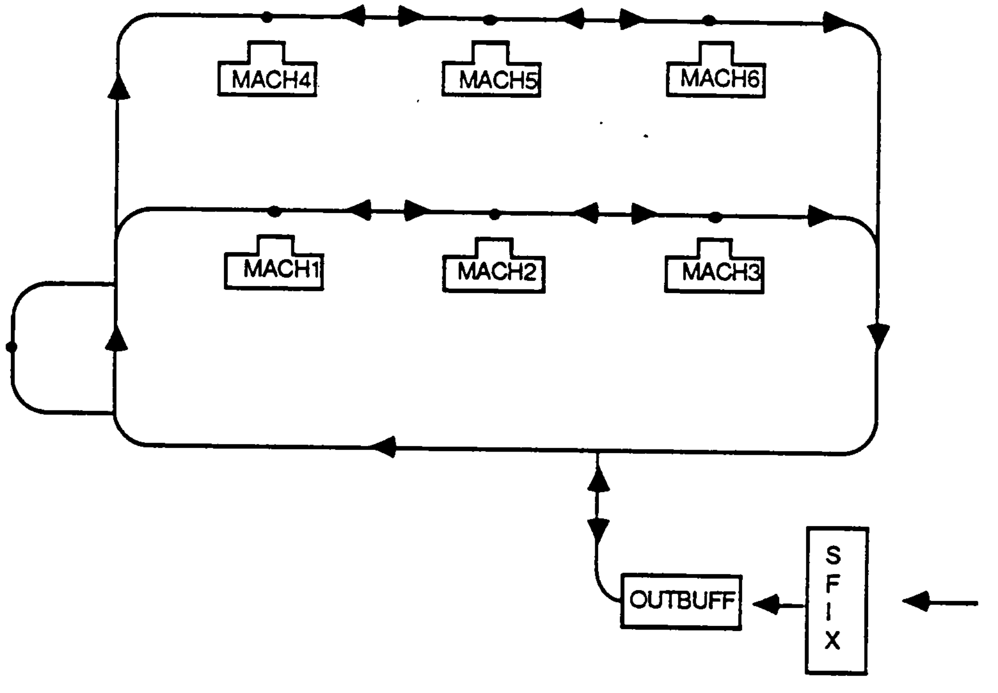


FIGURE 33. FMS/AGVS (2*3) WITH SOME BIDIRECTIONAL SEGMENTS

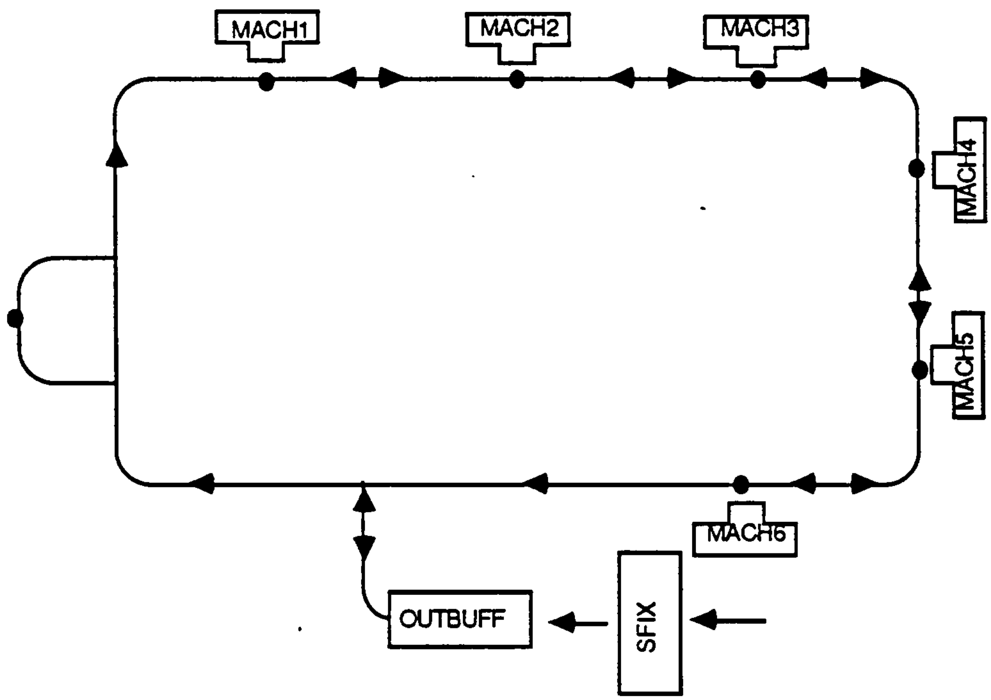


FIGURE34. FMS/AGVS 1*6, SINGLE LOOP LAYOUT WITH SOME BIDIRECTIONAL SEGMENTS

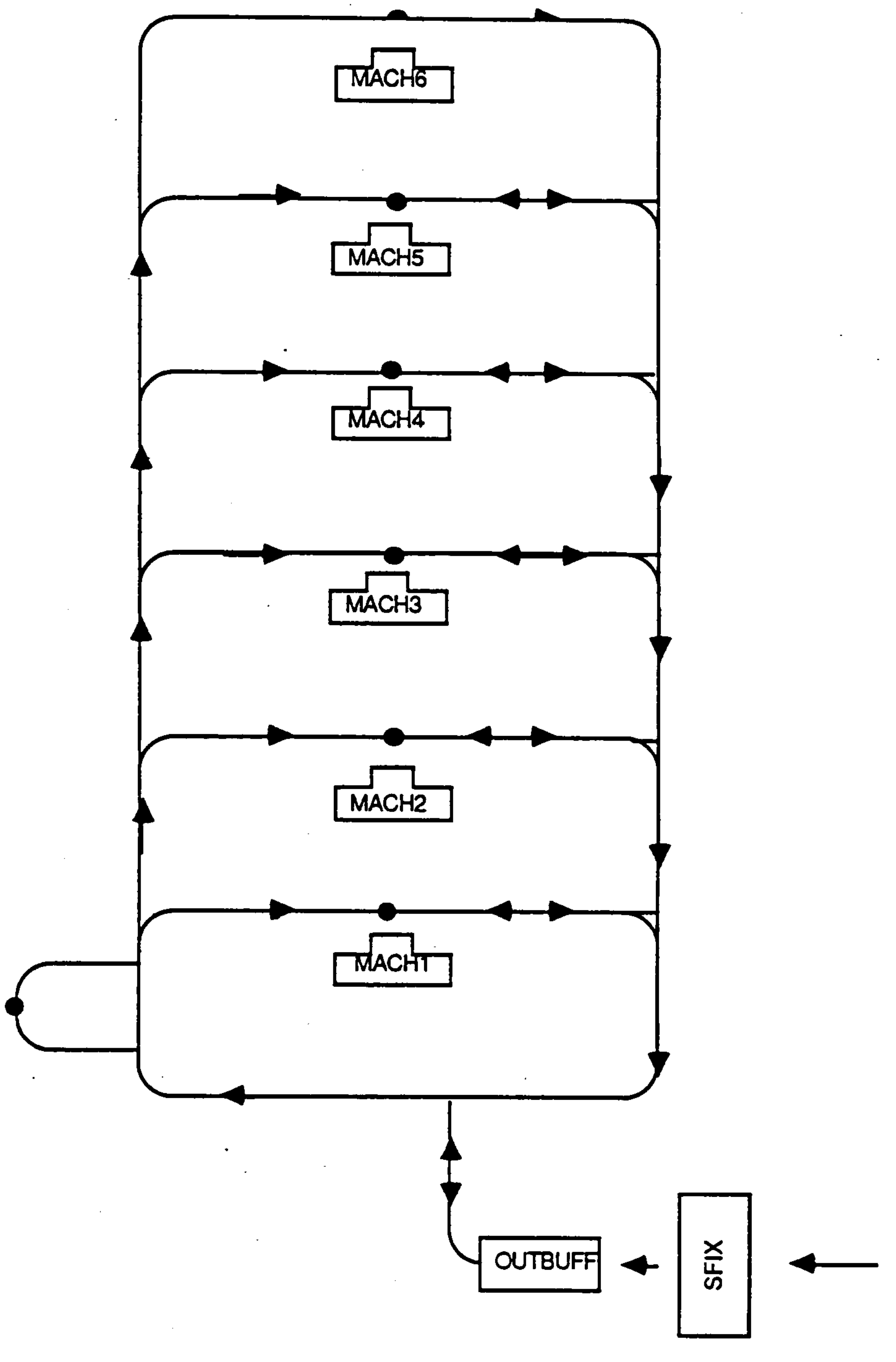
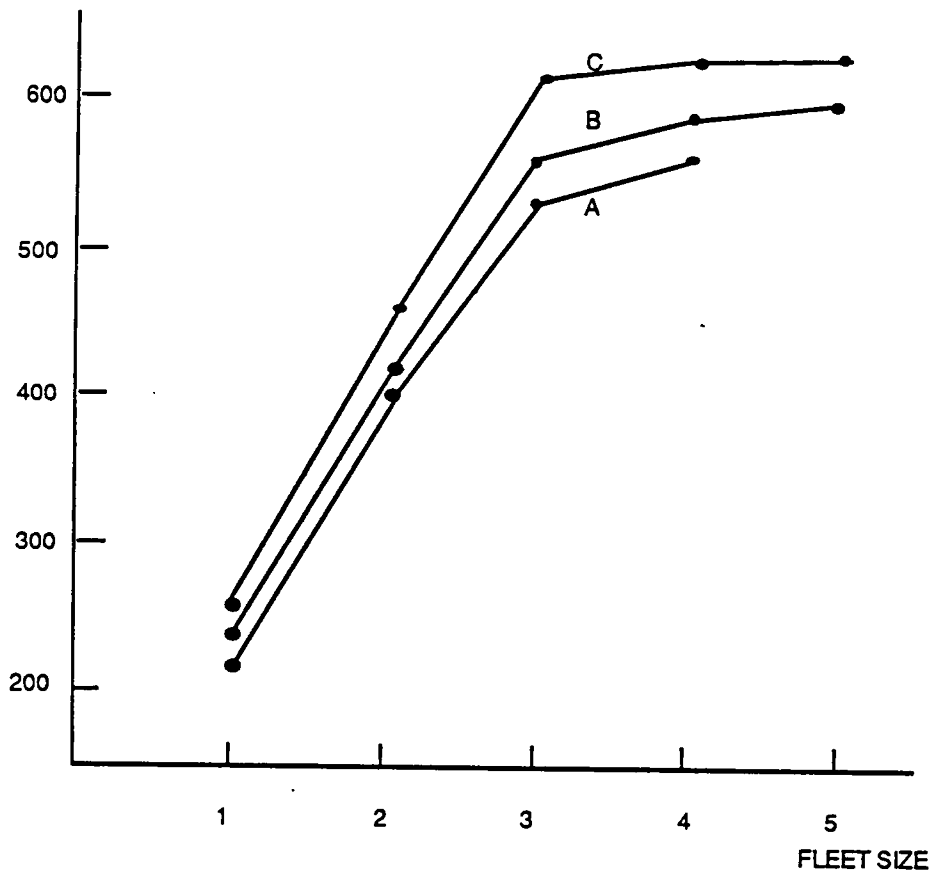


FIGURE 35. FMS/AGVS (6*1) LADDER LAYOUT WITH SOME BIDIRECTIONAL SEGMENTS



A : Routing
1- 1,2,3
2- 4,5,6

B: Routing
1- 3,2,1
2- 4,5,6

C: Routing
1- 3,2,1
2- 6,5,4

FIGURE 36. RELATIONSHIPS BETWEEN THROUGHPUT , FLEET SIZE, ROUTING IN BIDIRECTIONAL LAYOUT 6*1

speed levels makes the AGVS the bottleneck within the overall system.

It seems that the in line layout is not working, whereas other configurations used work relatively well. This illustrates a basic point in designing FMS which is to process several part types without re-arranging machine layout. This property is typically obtained with the use of return loops as they permit these systems to handle changes in routing sequences without incurring layout modifications. Another fact shown in the results is the problem of optimal fleet size. The intuition that not enough vehicles, as well as too many of them, may cause throughput to drop seems to be verified. This problem exists even for simple systems using relatively small fleet sizes, and it becomes more acute for a system such as the six loop system.

The main factor when vehicle speed is low seems to be distance traveled. This is shown by the results (Table 4.) of the single loop layout whose performance does not fall too much as routing is modified. However, this is true only for fleet sizes of two and three. Below or beyond this range throughput falls considerably, thus showing the sensitivity of system performance to fleet size. The situation is slightly different for the double loop layout (Figure 25). Results displayed in Figure 29 show that performance degrades rapidly as routing is modified except for fleet size of three for which throughput does not fall too much (relatively speaking). The situation becomes even more critical with the six loop layout (Figure 31) . In this case, throughput remains virtually unaffected by routing changes as distance (and load) traveled by vehicles is not changed for different routings. The six loop layout has the property that the load in terms of vehicle hours is not affected by routing modifications, as long as these modifications remained within certain limits.

It should be noted at this point that routing flexibility has been defined in a particular fashion, namely, the ability to respond to routing changes. However, these changes were in a minor way, as the part mix remained unchanged, and most important, each routing had a distinct set of machines. In other words, no overlap existed between job type as far as machine utilization was concerned. If routings were intertwined, (for example, Job type 1: 1-2-3 and Job type 2: 3-2-1), then shop locking would occur with the current manufacturing model under study. In order to study the routing flexibility involving such routing complexity a system involving more sophisticated control procedures must be used. Such procedures might include look ahead capability or more reactionary types such as rerouting schemes. Modifications to the material handling system, such as adding input and output buffers to cells or the use of a central storage, may be necessary.

The bi-directional case seems to be illustrating the superiority of the multiple loop layout over the single or double loop layouts when the segments that link cells to the main loop are allowed to be bi-directional. By having a rung dedicated to a single cell or machine, vehicles have time to load and unload parts without encountering other vehicles on the way. The single loop fails almost completely as it appears that contention rules do not resolve the problem of excessive blocking. The double loop layout fairs slightly better, but blocking occurs in half the cases. Only the six loop layout sees its performance improved with bi-directional layouts. However, this improvement is limited to certain routings (namely, routing C and B). Routing A, does not profit from the bi-directional segments because of the disposition of machines. Finally, it could be said that the optimal fleet size for this particular configuration is four, as it maximizes throughput and minimizes throughput degradation for routing perturbations.

Flexibility indices were developed in Chapter V. It was said that flexibility might be measured by the concept of elasticity which links the response of a system to parameter disturbances. This measure can be applied to continuous (such as vehicle speed) and discrete variables (such as fleet size). However, it appears that disturbances such as changes in routing are more difficult to quantify, as routing is not a variable but a combinatorial problem. Nevertheless, the previous results can shed some light in measuring the effect of routing.

Performance measures regarding flexibility are directly related to the definition itself of what makes a system flexible. Volume flexibility (VF) with respect to fleet size can be measured with the following index:

$$VF = \frac{\Delta V/V}{\Delta FT/FT}, \text{ (where V is throughput and FT fleet size)}$$

With respect to V (which can be considered as the base demand or starting throughput with fleet size of one), this type of index can be used in two ways. First, the value of V can be defined as the throughput of the system corresponding to a fleet size of one, and depends on the routing considered. Secondly, V can be set as the lowest throughput among layouts when routing A is involved (namely 199 units). This value is then used in all calculation of VF. Given the data in Table 4, the indices can be computed (according to the first way) for the three layouts (for routings A ,B and C).

Routing A:

Single loop: $$VF = \frac{(590-323)/323}{(4-1)/1} = 0.28$$

Double loop: $VF = \frac{\underline{(613-240)/240}}{(4-1)/1} = 0.52$

Six loop: $VF = \frac{\underline{(567-199)/199}}{(4-1)/1} = 0.62$

<u>Routing B</u>:

Single loop: $VF = \frac{\underline{(594-269)/269}}{(4-1)/1} = 0.40$

Double loop: $VF = \frac{\underline{(587-207)/207}}{(4-1)/1} = 0.61$

Six loop: $VF = \frac{\underline{(571-198)/198}}{(4-1)/1} = 0.62$

<u>Routing C</u>:

Single loop: $VF = \frac{\underline{(576-234)/234}}{(4-1)/1} = 0.49$

Double loop: $VF = \frac{\underline{(561-178)/178}}{(4-1)/1} = 0.72$

Six loop: $VF = \frac{\underline{(571-198)/198}}{(4-1)/1} = 0.63$

With this particular use of the indices, the six loop layout appears more flexible (for routings A and B). This way of measuring flexibility (by looking at differences) can indicate the rate of improvement that a system can attain with changes in its characteristics. The other way to compare these same layouts is to use a base demand of 199 units and a base fleet size of one in the indices (See Table 6 and Figures 37, 38 and 39). Again, rates of improvements are measured. In this case, routing A is the most favorable case in terms of work load (vehicle-hours) imposed on the AGVS. When routing C is involved, the flexibility figures are slightly lower, since the FMS is less able to increase throughput for the same increase in fleet size. When using a base demand,

TABLE 6. FLEXIBILITY AS A FUNCTION OF FLEET SIZE

1*6 : SINGLE LOOP LAYOUT
2*3: DOUBLE LOOP LAYOUT
6*1: SIX LOOP LAYOUT

INCREASE IN FLEET SIZE		1	2	3
ROUTING A	1*6	1.59	0.92	0 .65
	2*3	1.34	0.99	0.69
	6*1	0.95	0.84	0.62
ROUTING B	1*6	1.40	0.91	0.66
	2*3	1.12	0.89	0.65
	6*1	0.95	0.84	0.62
ROUTING C	1*6	1.17	0.86	0.63
	2*3	0.87	0.69	0.61
	6*1	0.95	0.84	0.62

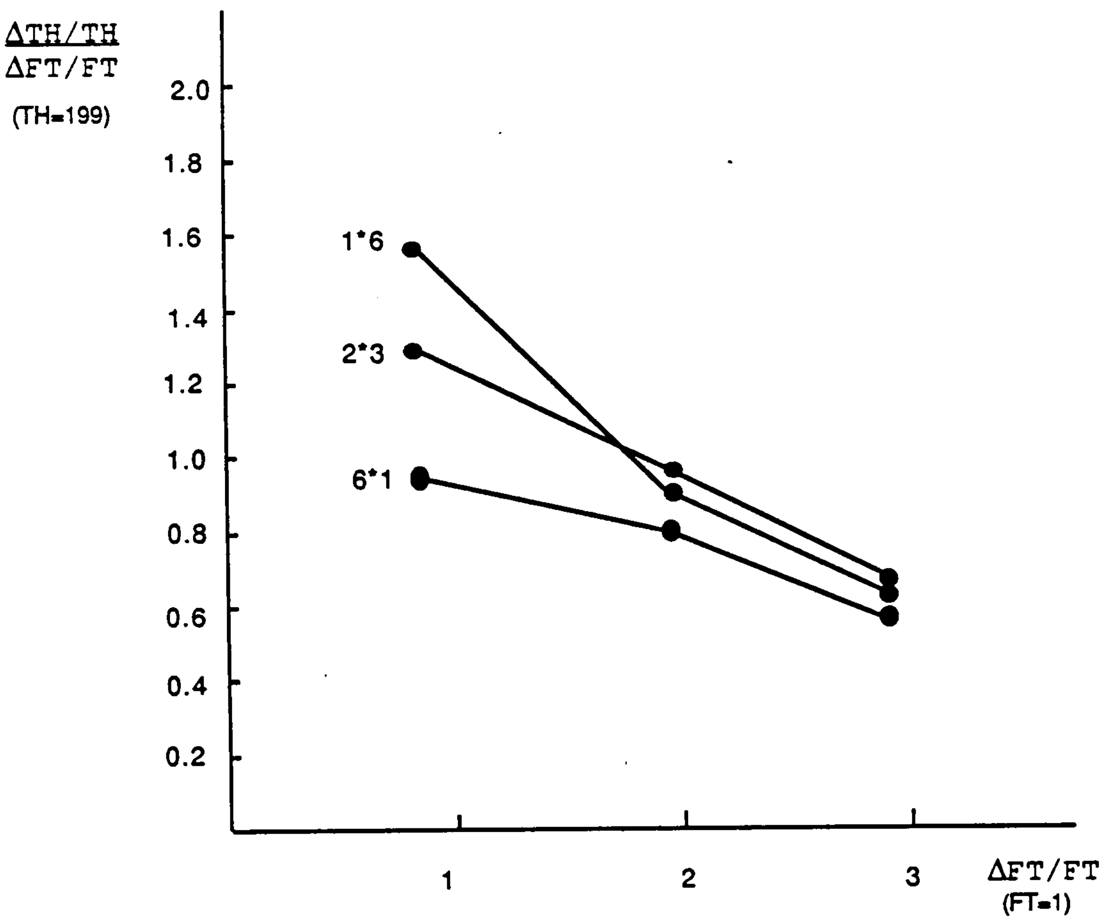


FIGURE 37. FLEXIBILITY AS A FUNCTION OF CHANGE IN FLEET SIZE
ROUTING A

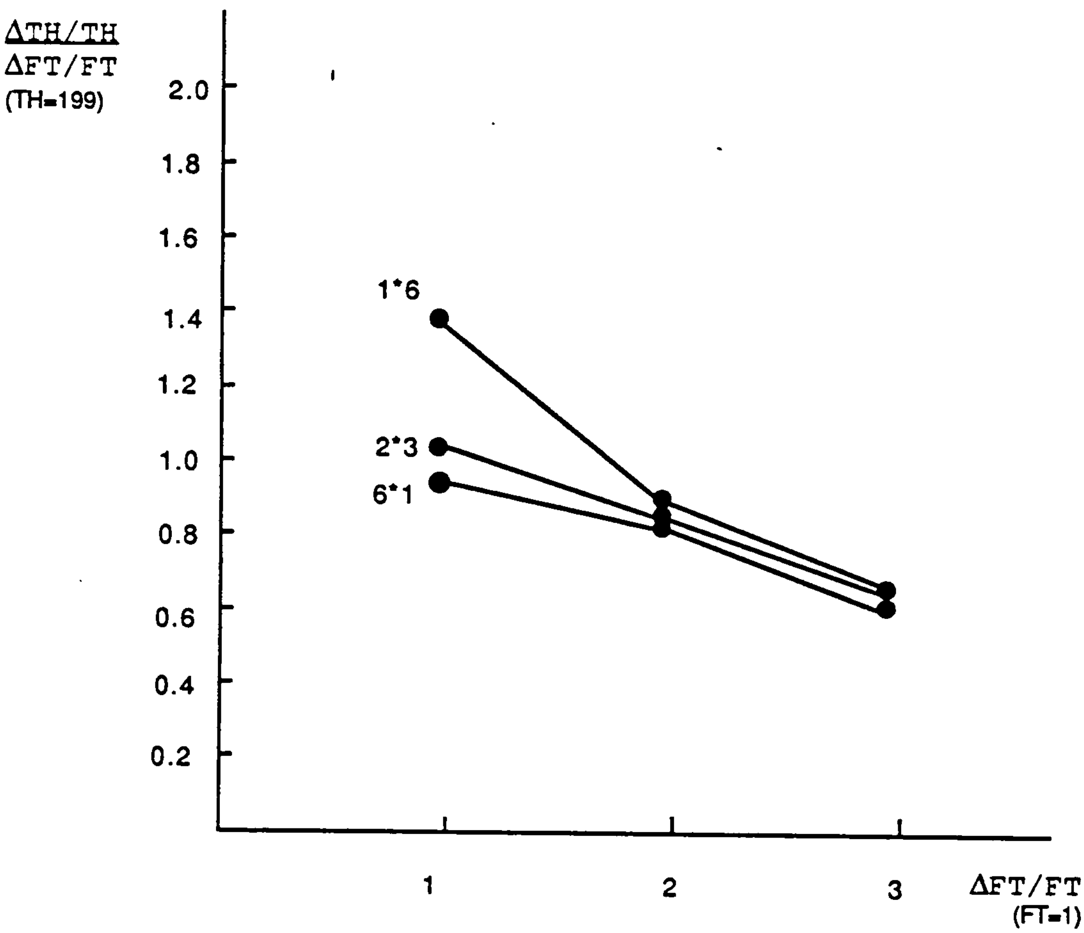


FIGURE 38. FLEXIBILITY AS A FUNCTION OF CHANGE IN FLEET SIZE
ROUTING B

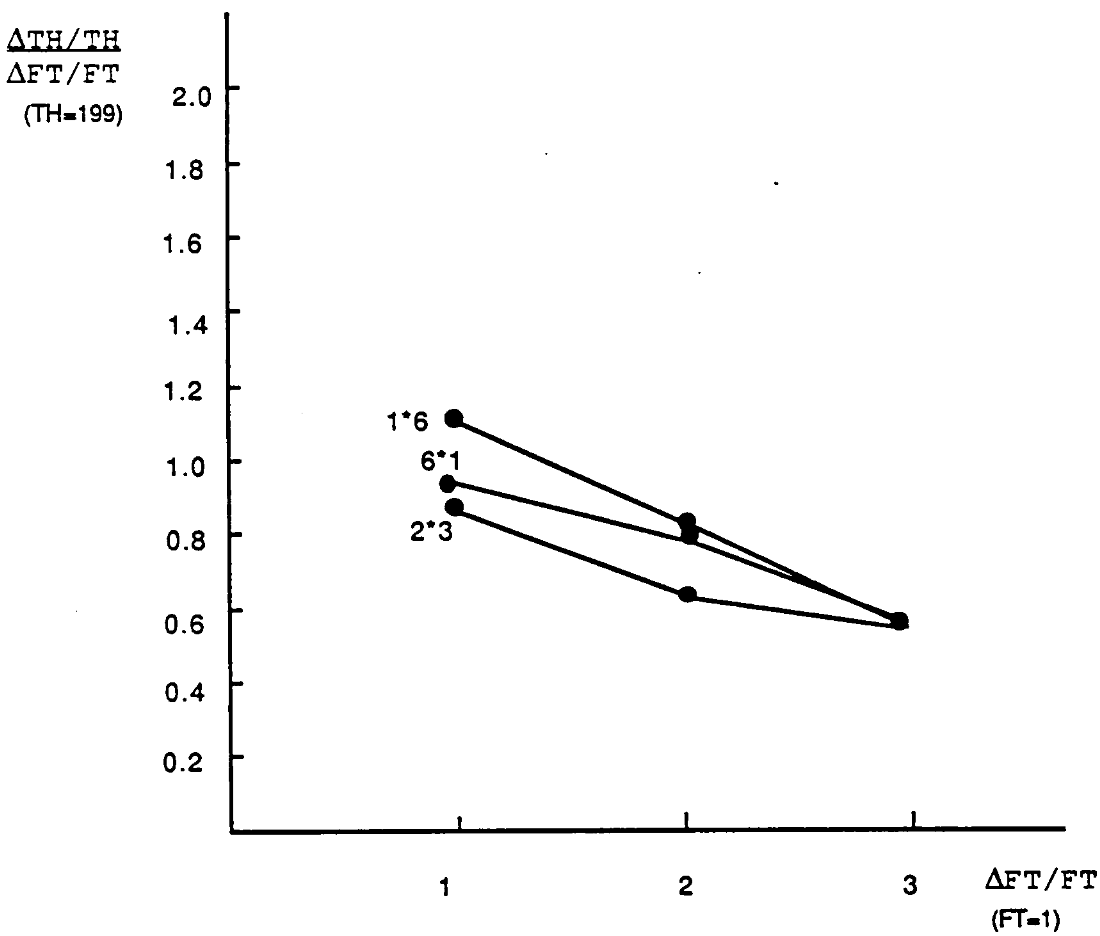


FIGURE 39. FLEXIBILITY AS A FUNCTION OF CHANGE IN FLEET SIZE
ROUTING C

these results seem to indicate that the single loop layout has the ability to increase throughput at a higher rate than the other layouts (for routings B and C). The six loop layout comes last in this regard (for routings A and B). The use of this index appears complex as different results are obtained depending on how the parameter V is defined. The first way uses the index on a relative basis, whereas the second includes a base throughput common to all layouts so that they can be compared on an more absolute basis.

Table 6 and Figures 37, 38 and 39 give additional flexibilities for different ranges of $\Delta\dot{F}$ (change in fleet size). According to these figures, the rate of improvement in terms of throughput decreases as more and more vehicles are added in the FMS. A fourth vehicle could have been added to the system. In this case, with fleet size of five, the throughput starts to decrease. The flexibility index becomes negative and would have been lying under the horizontal axis (in Figures 37, 38 and 39). This decreasing behavior poses a problem, since the more flexible a system is, the higher its associated flexibility index should be. Clearly, this is not the case here with these elasticity indices. Some transformation on this type of index is likely to be required so that it can be linked to the opportunity costs the way it was assumed in Section VI-1. This index mainly show the rate of improvement which is attained with a particular configuration. It does not provide any cut off point beyond which further investment in flexibility is justified (from a technical point of view).

VIII-6 VOLUME FLEXIBILITY: PMHS & PCP

The base model studied so far indicates that the particular FMS involved here has a capacity of 666 units for a 200,000 seconds run. This figure was obtained by simulating the base model with "high" speed vehicles (6 ft/sec.). Tables 7, 8, 9, and 10 as well as Figures 40 to 42 portray the relationships between efficiency , PMHS, (percentage of perfect MHS) and effectiveness, PCP, (percentage of perfect capacity), for the base model for different layouts, fleet sizes and vehicle speed. In general , it can be seen that PMHS and PCP increase together but at a decreasing rate, illustrating again the idea of decreasing returns as more and more resources are input into the system. A certain limit seems to be attained at a certain point. The faster the system can reach that limit the more flexible it will be in the sense that it uses less resources for the same improvement in effectiveness. For instance, an FMS having higher AGV speed is therefore more flexible than another one with lower AGV speed, as the former does not have to increase its fleet size as much as the latter one. (See Figure 43.).

VIII-7 FLEXIBILITY AND SYSTEM CAPACITY

The above preliminary discussion highlights the problem associated with defining operationally what is meant by flexibility. If throughput or lead time is paramount in the evaluation of flexibility of a manufacturing system then, by inspecting Table 4, the single loop layout is the most desirable, since it dominates the other ones in almost all situations. If product variety is the main performance criterion, then the choice is not so clear, since all three layouts can process the three types of routing. But, again if one looks at throughput, then the single loop layout is still preferable since, as it was noticed, it is the most resilient to routing changes.

Another type of routing flexibility measurement can be observed when it is realized that the product range can be

TABLE 7 EFFICIENCY, EFFECTIVENESS AND FLEXIBILITY ; LAYOUT 1*6
(AGV SPEED 3.0 3.5)

ROUTING A						
FLEET SIZE	MACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	127	4023	11.74	48.5
2	600	360	127	2264	17.91	77.33
3	600	360	127	1792	21.84	84.83
4	600	360	127	1677	21.71	88.59
ROUTING B						
FLEET SIZE	MACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	238	4885	9.86	40.39
2	600	360	238	2484	16.30	71.62
3	600	360	238	1817	19.9	84.38
4	600	360	238	1679	21.86	89.19
ROUTING C						
FLEET SIZE	MACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	356	5719	8.53	35.14
2	600	360	356	2967	14.01	64.71
3	600	360	356	1974	18.24	81.23
4	600	360	356	1698	19.90	86.49

TABLE 8 EFFICIENCY, EFFECTIVENESS AND FLEXIBILITY ; LAYOUT2*3
(AGV SPEED 3.0 3.5)

ROUTING A						
FLEET SIZE	M ACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	141	5892	8.58	36.04
2	600	360	141	2727	15.67	69.97
3	600	360	141	1802	20.67	89.19
4	600	360	141	1631	21.96	92.04
ROUTING B						
FLEET SIZE	M ACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	267	6836	7.44	31.08
2	600	360	267	3058	14.00	63.36
3	600	360	267	1942	18.93	83.18
4	600	360	267	1673	20.69	88.14
ROUTING C						
FLEET SIZE	M ACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	419	7858	6.5	26.88
2	600	360	419	3503	12.29	56.01
3	600	360	419	2454	15.65	70.87
4	600	360	419	1781	18.99	84.23

TABLE 9 EFFICIENCY, EFFECTIVENESS AND FLEXIBILITY ; LAYOUT 6*1
(ALL ROUTINGS , AGV SPEED 3.0 3.5)

FLEET SIZE	M ACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	1049	6943	6.7	29.88
2	600	360	1049	3233	11.45	58.41
3	600	360	1049	2123	14. 52	80.03
4	600	360	1049	2086	14.65	85.14

TABLE 10. EFFICIENCY, EFFECTIVENESS AND FLEXIBILITY ; LAYOUT1*6
VARIATIONS IN AGV SPEED (ROUTING A)

AGV SPEED 4.5 4.0						
FLEET SIZE	MACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	90	3502	13.16	55.26
2	600	360	90	1912	20.26	85.94
3	600	360	90	1644	22.27	90.29
-	-	-	-	-	-	-
AGV SPEED 5.5 5.0						
FLEET SIZE	MACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	72.9	3385	13.58	58.56
2	600	360	72.9	1678	22.14	93.19
-	-	-	-	-	-	-
-	-	-	-	-	-	-
AGV SPEED 6.5 6.0						
FLEET SIZE	MACH. TIME	L/U TIME	TRAVEL T.	WAIT TIME	PMHS (%)	PCP (%)
1	600	360	60.5	3411	13.54	59.86
2	600	360	60.5	1712	21.96	93.59
-	-	-	-	-	-	-
-	-	-	-	-	-	-

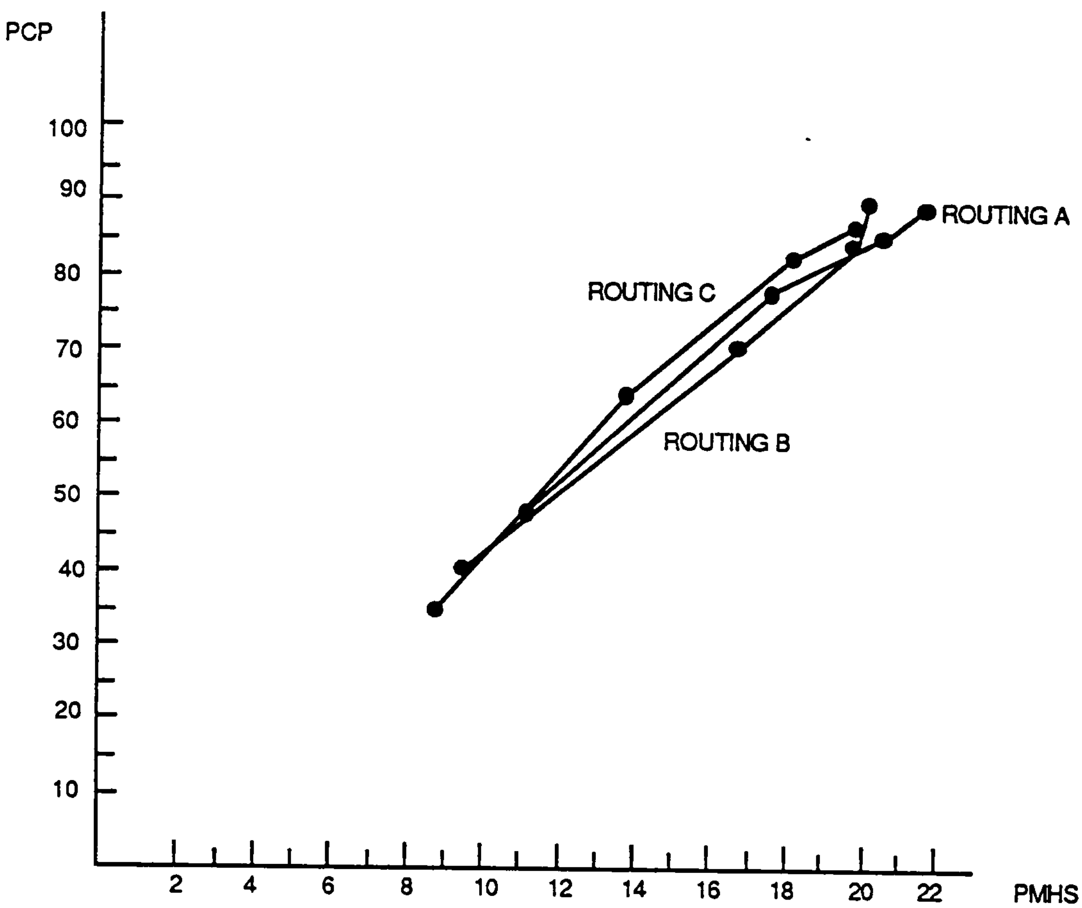


FIGURE 40. FLEXIBILITY, EFFICIENCY AND EFFECTIVENESS (LAYOUT 1*6)

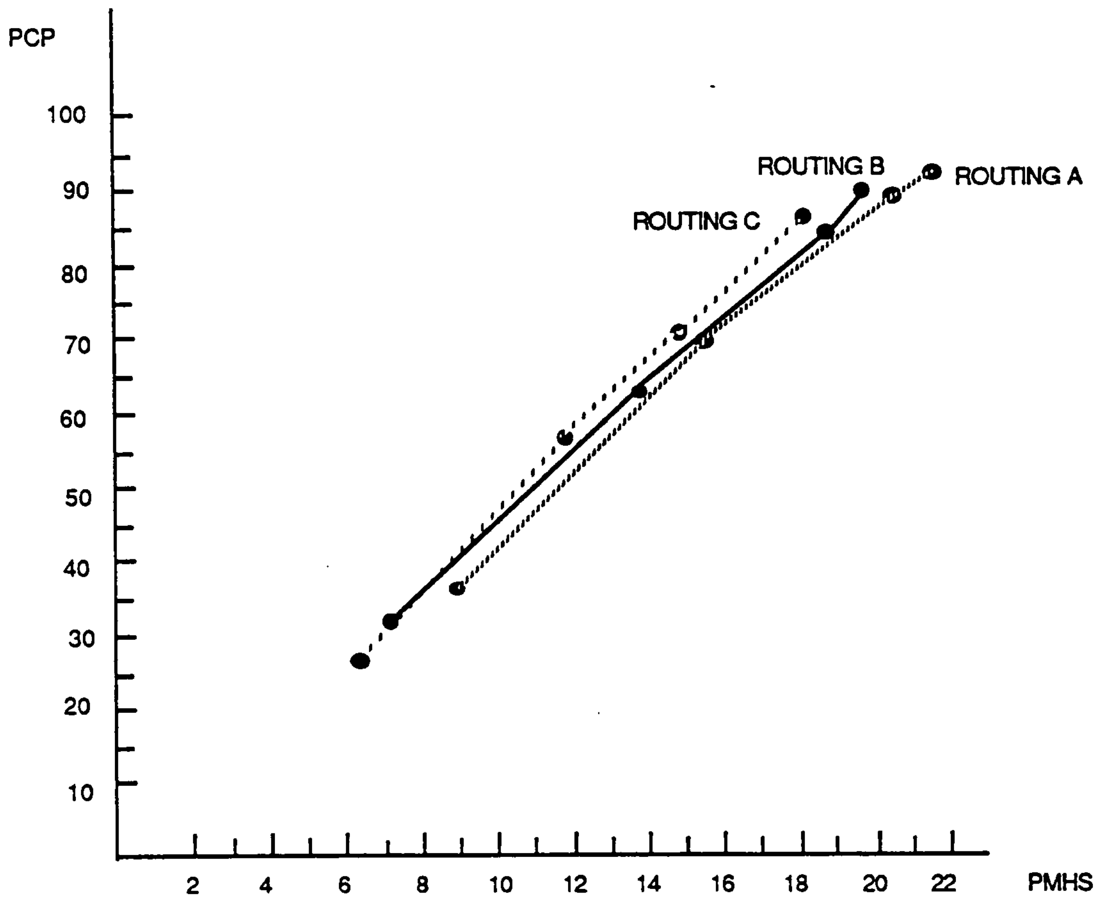


FIGURE 41 . FLEXIBILITY, EFFICIENCY AND EFFECTIVENESS (LAYOUT2*3)

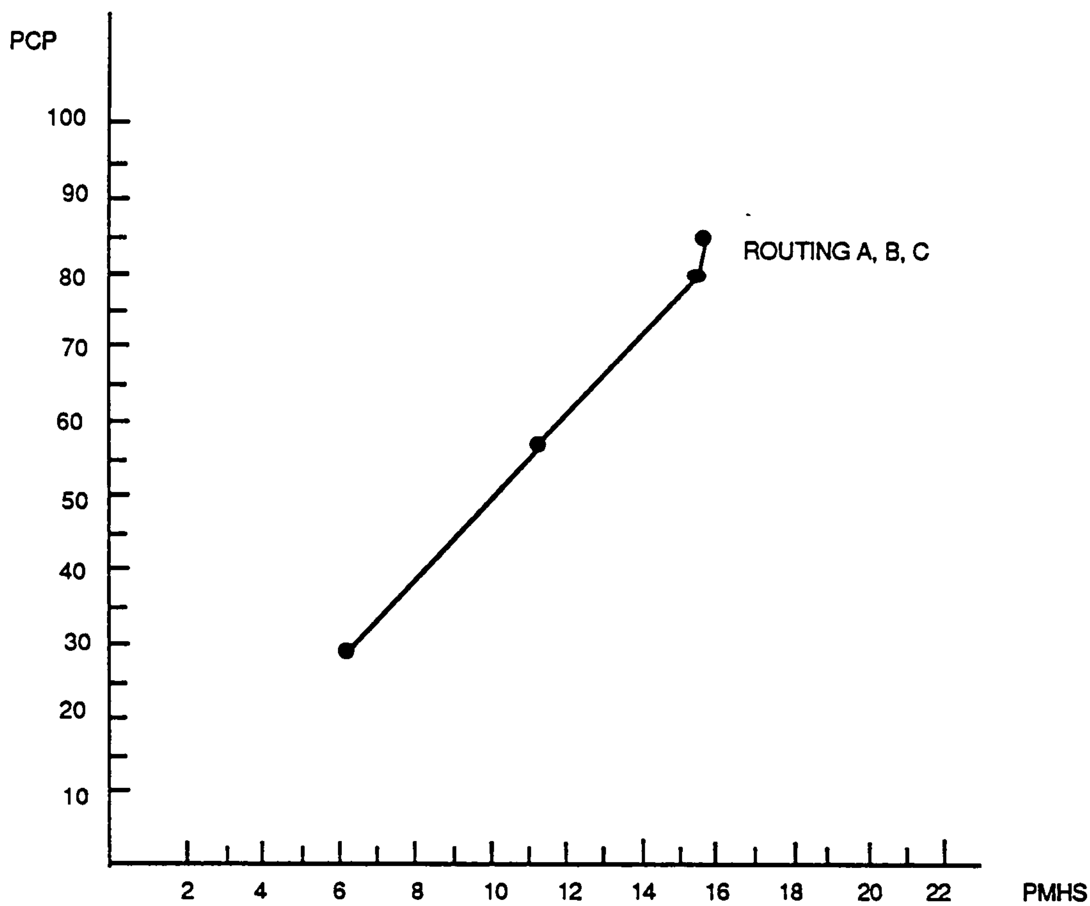


FIGURE 42. FLEXIBILITY, EFFICIENCY AND EFFECTIVENESS (LAYOUT 6*1)

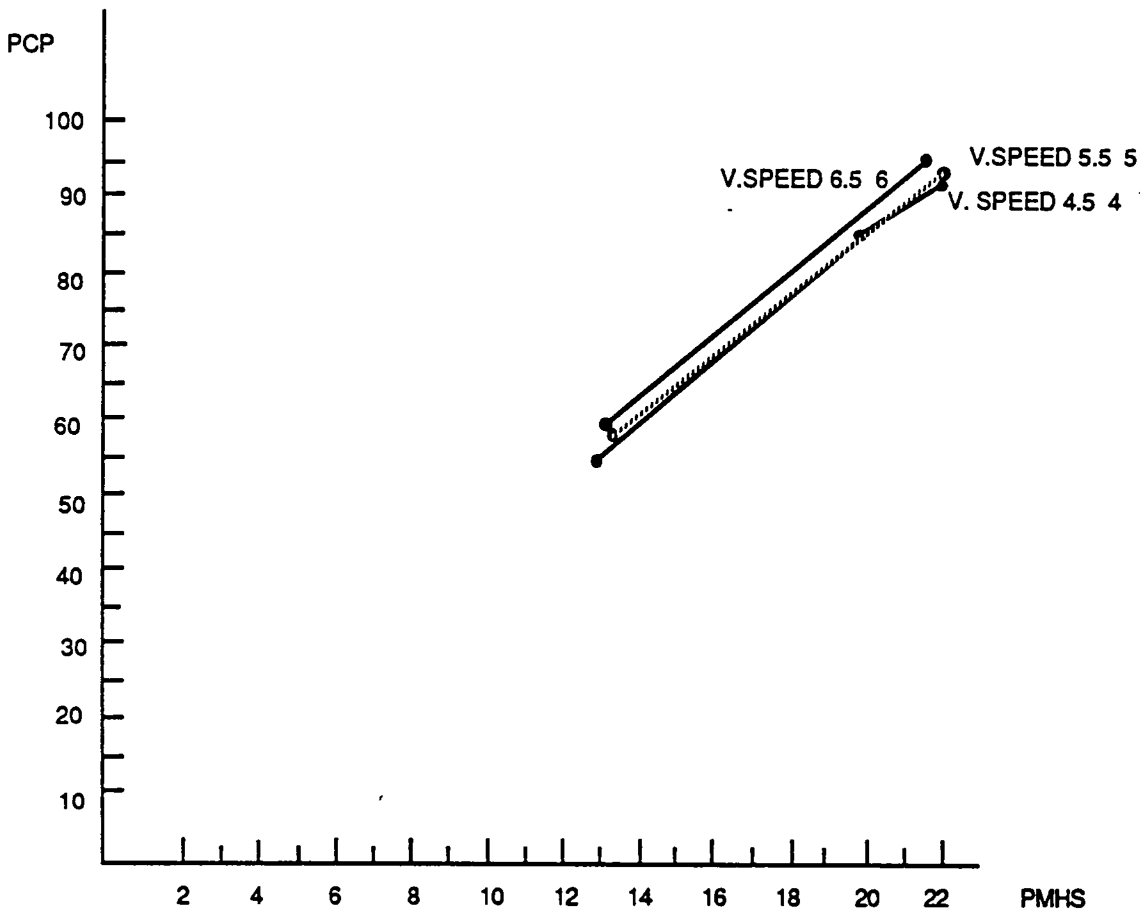


FIGURE 43. FLEXIBILITY, EFFICIENCY AND EFFECTIVENESS OF LAYOUT 1*6 VARIATIONS IN SPEED (ROUTING A)

increased. Instead of having two job types, the FMS may have to process four, six, or eight different jobs. This idea will be explored further in a subsequent section.

The main conclusion up to now is that from a system capacity point of view, volume and routing flexibility go hand in hand. When optimizing for volume flexibility, one also optimizes for routing flexibility. There will always be this trade off between producing at a high volume and low variety, and producing at a low volume and high variety for a given overall capacity. However, a system such as the single loop layout which was thought to favor volume flexibility also performs well with respect to routing flexibility.

As with any system, maximizing capacity involves dealing with bottlenecks. The determination of the bottleneck of a flexible manufacturing system is itself a problem that is complex, since such a system is the result of the *coupling* of two sub-systems, namely, the cells or machines and the MHS. Each of these two sub-systems have a *capacity* per se. And, in a sense, the less *efficient* of these two will constitute a *bottleneck* within the overall FMS. If the MHS is not sufficiently efficient in the face of rising demand and is thus the constraining factor with respect to throughput, then increasing fleet size may solve the problem. However, this particular counteraction may not be sufficient as the MHS reaches its optimal size. Vehicle speed may have to be increased. In turn, these two improvements may still not be adequate. Loading and unloading times may be too long. Another component that may have to be added is input and output buffers which (as it will be seen later) have a significant effect in the effectiveness of an FMS.

The problem is that, even though the MHS and the cells themselves can be very efficient, their coupling can produce an overall system that is not that efficient. For instance, the fact that an FMS does not have input and output buffers restricts the number of parts that can be in the system simultaneously. The cells can be efficient in processing loads, and the MHS can be efficient as well in bringing them to the machines, but these loads have to wait nevertheless at the fixturing station until a machine is freed, which may take time. This problem dissolves when input and output buffers are added to the material handling system, since loads can be routed to the machines instead of waiting at different points in the layout. The reduction of these delays improves the FMS performance and its flexibility.

VIII-8 ROUTING FLEXIBILITY

So far, routing flexibility has been measured in terms of decrease in throughput as a result of an increase in load on the AGVS. The more resilient the system is to changes in routing, the more flexible is the system.

Another concept associated with routing is that of product mix or number of different products which can be processed by the system. If it is assumed that a particular product has one particular routing, then there is a simple relationship between routing flexibility and product mix. A system will be more flexible (from a routing point of view), if it can accommodate a larger product range.

If the double loop layout is in fact a transfer line with some automatic transfer devices between machines 1,2,3 and machines 4,5,6, then the number of different products that it could process would be only two (given a three machine or three stage routing). For other product mixes, the machine layout of such a system would have to be changed. This of course does not happen with an FMS. Several types of routing can be accommodated with the base model. The FMS studied so far are able to cope with several routings, even though the addition of new products limits the individual amount of each of these that can be produced.

There are still routing limitations associated with the systems studied so far. If, for example, one attempts to run the base model with routings such as A:1,2,3; B:3,2,1; C:4,5,6; and D:6,5,4 a system deadlock will occur. This is due to the overall structure that governs the pattern of events within the base model. As vehicles cannot be requested as machines are freed, a deadlock is sure to occur. In this case, an entity at machine 1 requests machine 2 where another entity waits simultaneously for machine 1 to be freed. At this point, these two machines are in a deadlock, and this situation cannot be remedied unless some sort of shop unlocking procedure is imbedded in the FMS.

In other words, as long as the flow of parts in the base model is unidirectional, the FMS will be processing the part whatever the layout. As soon as cycles occur within routings (or backtracking), the base model is incapable of processing simultaneously all parts.

Another aspect of routing flexibility is machine breakdown. In this particular case, flexibility is the ability of an MHS to reroute a part to another machine that can process it. Apart from control mechanisms that have to be present in the FMS in order to respond in a real time basis to routing changes, machines must be able to absorb the increase in load. In other words, for flexibility of routing from a machine breakdown to be possible, machines must be *underutilized*. If an MHS is able to use machines close to their capacity, then throughput will diminish even though parts are effectively routed to the other machines. These machines, if already used near their capacity, will become bottlenecks when they have to absorb a load increase.

VIII-9 FMS WITH INTERSTATION BUFFERS

In order to correct the weakness (in terms of product mix capability) of the preceding system, input and output buffers can be added to the machines or cells within the existing layouts. The internal logic of the model is modified in that vehicles can be requested before machines without any concern as to whether the next machine is available or not. It is assumed that buffers are sufficiently large to absorb incoming parts and outgoing ones. This will have the effect that all types of three stage routings will be processed by the FMS. As a side effect, the volume of parts that can be processed by this new FMS is substantially higher than the one without buffers. Again, the idea comes to mind that optimizing for either volume or routing flexibility has the effect of improving both flexibilities .

This type of FMS illustrates the idea of *overlapping* , which is the capability of a system to process several parts simultaneously. It was said earlier that throughput was a function of lead time and overlapping. From simulation results it appears that the FMS with buffers has a superior overlapping capability over the one without buffers, since it can process more parts with an efficiency index (PMHS) lower than the one associated with the base model. This means that parts have a longer sojourn time in the system, but there are more of them in it. The main increase in lead time is due to the time parts spend in output buffers waiting for vehicles. Of course this waiting can be reduced (as for the base model) by increased fleet size or vehicle speed, which will have the effect of reducing the lead time and increasing the efficiency index.

The FMS with input and output buffers therefore appears more flexible, since it uses less AGVS resources for the same environmental conditions than the base FMS. On the other hand; it uses a secondary material handling system; namely, input and output buffers.

Results of simulation runs are illustrated in Tables 11 through 14. One run of 200000 seconds was done for each case (that is, for a given fleet size) with input demands exponentially distributed with mean interarrival time of 150 seconds.

Tables 11 to 14 show the performance of AGVS from a blocking perspective. Layouts 1*6 (single loop) and 6*1 (ladder layout) with input and output buffers can be compared in terms of throughput. Blocking, like the other parameters measured in these tables, is computed by the ratio of vehicle-seconds (during which vehicles are blocked) to the total run time (in seconds) of the simulation (Pritsker, 1986). Tables 11 and 12 are for routing A, and Tables 13 and 14 are for routing C. Tables 11 through 14 include statistics that pertain essentially to the load imposed on the AGVS fleet as a whole. Estimates of these statistics pertaining to individual vehicles can be easily obtained by dividing the figures in the tables by the fleet size.

The first set of output statistics is called vehicle utilization and describes the use of the fleet of vehicles when they are assigned to travel to pick up or drop off loads, and when they are in loading and unloading states. The other set of statistics refers to *how well* the FMS uses the AGVS. Blocking (in

Table 11. Vehicle performance for layout 1*6 with buffers, routing A

		VEHICLE UTILIZATION (In vehicle sec/sec)					BLOCKING AND IDLE TIME (In vehicle sec/sec				
Fleet size	Through-put	Traveling to load (empty)	Loading	Traveling to unload (full)	Unloading	Total productive	Traveling empty blocked	Traveling full blocked	Traveling idle	Stopped idle	Total non-productive
1	295	0.273	0.274	0.178	0.274	0.999	0.0	0.0	0.0	0.001	0.001
2	578	0.494	0.53	0.348	0.529	1.901	0.063	0.032	0.001	0.002	0.099
3	798	0.721	0.728	0.477	0.728	2.655	0.241	0.098	0.004	0.003	0.345
4	1003	0.905	0.913	0.598	0.913	3.33	0.466	0.193	0.008	0.004	0.67
5	1174	1.083	1.068	0.700	1.067	3.919	0.761	0.298	0.017	0.005	1.081
6	1288	1.178	1.170	0.766	1.170	4.284	1.137	0.46	0.097	0.022	1.716

Table 12. Vehicle performance for layout 6*1 with buffers, routing A

		VEHICLE UTILIZATION (In vehicle sec/sec)					BLOCKING AND IDLE TIME (In vehicle sec/sec)				
Fleet size	Through-put	Traveling to load (empty)	Loading	Traveling to unload (full)	Unloading	Total productive	Traveling empty blocked	Traveling full blocked	Traveling idle	Stopped idle	Total non-productive
1	287	0.255	0.267	0.211	0.266	0.999	0.0	0.0	0.0	0.001	0.001
2	578	0.451	0.529	0.421	0.529	1.928	0.046	0.022	0.002	0.002	0.072
3	843	0.658	0.769	0.608	0.768	2.803	0.126	0.063	0.004	0.004	0.197
4	1072	0.847	0.977	0.775	0.976	3.575	0.259	0.153	0.010	0.004	0.425
5	1277	1.001	1.162	0.921	1.161	4.244	0.452	0.270	0.026	0.008	0.756
6	1324	1.048	1.204	0.954	1.203	4.409	0.645	0.382	0.435	0.129	1.591

Table 13. Vehicle performance for layout 1*6 with buffers, routing C

		VEHICLE UTILIZATION (In vehicle sec/sec)					BLOCKING AND IDLE TIME (In vehicle sec/sec				
Fleet size	Through-put	Traveling to load (empty)	Loading	Traveling to unload (full)	Unloading	Total productive	Traveling empty blocked	Traveling full blocked	Traveling idle	Stopped idle	Total non-productive
2	429	0.401	0.396	0.762	0.395	1.954	0.021	0.022	0.001	0.002	1.046
4	815	0.748	0.743	1.431	0.743	3.665	0.150	0.174	0.007	0.004	0.335
6	1130	1.023	1.029	1.981	1.028	5.061	0.392	0.522	0.019	0.006	0.939
8	1295	1.219	1.179	2.269	1.178	5.845	0.855	0.968	0.266	0.066	2.155
10	1329	1.307	1.206	2.320	1.204	6.037	1.313	1.329	1.082	0.238	3.963
-	-	-	-	-	-	-	-	-	-	-	-

Table 14. Vehicle performance for layout 6*1 with buffers, routing C

		VEHICLE UTILIZATION (In vehicle sec/sec)					BLOCKING AND IDLE TIME (In vehicle sec/sec)				
Fleet size	Through-put	Traveling to load (empty)	Loading	Traveling to unload (full)	Unloading	Total productive	Traveling empty blocked	Traveling full blocked	Traveling idle	Stopped idle	Total non-productive
2	521	0.399	0.478	0.581	0.477	1.935	0.029	0.032	0.002	0.002	0.065
4	963	0.767	0.878	1.071	0.878	3.593	0.189	0.206	0.008	0.004	0.407
6	1287	1.011	1.170	1.431	1.169	4.781	0.505	0.562	0.121	0.032	1.219
8	1333	1.048	1.207	1.474	1.206	4.936	0.871	0.809	1.100	0.286	3.064
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-

vehicle sec/sec) measures a certain type of flexibility associated to a given layout and is related to throughput in a complex way. If blocking increases, throughput will not necessarily decrease. As can be seen from these tables, by increasing fleet size, throughput increases even though blocking increases, as well. However, by comparing blocking statistics between layouts (Table 11 and 12), then it can be seen that for routing A, layout 6*1 is slightly superior in terms of throughput for a fleet size of one. For a fleet size of two, both layouts seem to be equivalent. However, for a fleet size larger than two the ladder layout dominates the single loop layout as blocking increases more rapidly for the latter one. The results are even more in favor of the ladder layout as routing C is imposed on the system. However, the situation in this last case is more complicated as the load in terms of travels are modified substantially. In effect, by looking at Tables 13 and 14, it can be seen that in the single loop layout it takes more time for the vehicles to reach their destination in order to unload parts (traveling to unload) than for the ladder layout (6*1). The problem of blocking, for the C routing, is not as important as it was for routing A. In fact, there is less blocking when routing C is involved than with routing A. These two examples show that modifying the layout will have, for a given routing, the effect of modifying the load on the AGVS and blocking patterns within the FMS configuration. Both of these must be assessed in order to correctly understand changes in throughput.

Another interesting statistic is AGVS idle time. This is another measure of how well the FMS uses its AGVS. In this particular case, idle time is fairly low indicating that the FMS uses its fleet of vehicles nearly all the time (See Tables 11 to 14). Compared with the base model, where parts have to wait for the next machine to be free before it can place a call for a vehicle, parts ask for a vehicle as soon as they free the machine they have just used. As a result, vehicle idle time is much higher when the FMS is without buffers (See Table 15).

So far no comparisons have been made between the base model (without buffers) and the system with buffers using the elasticity indices and the PMHS and PCP indices. If the elasticity index, ΔTH/ΔFT, were to be used, then the same base demand (199 units) would have to be used in order to make proper comparisons. In this case, the computations of this index for layout 1*6, routing A, are the following (throughput values are taken from Table 11):

$$VF = \frac{(578-199)/199}{(2-1)/1} = 2.9$$

$$VF = \frac{(798-199)/199}{(3-1)/1} = 1.51$$

$$VF = \frac{(1003-199)/199}{(4-1)/1} = 1.35$$

These values show that the system with buffers dominates the base model in terms of flexibility as its throughput climbs more rapidly. The use of the efficiency index for comparing these same two systems is more complex as overlap phenomena prevail in the system with buffers. This can be shown by computing the PMHS index for the layout (with buffers), testing, and comparing it to its counterpart associated with the base. For example, for layout 1*6 with buffers and a fleet of six vehicles (from Table 11), the throughput obtained is 1288 units. Again, in order to make a proper comparison between the two systems, the capacity of the base model (666 units), will be used for the effectiveness index PCP. In this particular case, PMHS is equal to 25% and PCP is, 193%. Again, these figures confirm that the system with buffers does a better job of using its AGVS than the system without buffers, even though

Table 15. Vehicle performance for layout1*6 no buffers, routing A

		VEHICLE UTILIZATION (In vehicles)					BLOCKING AND IDLE TIME (In vehicle				
Fleet size	Through-put	Traveling to load (empty)	Loading	Traveling to unload (empty)	Unloading	Total productive	Traveling empty blocked	Traveling full blocked	Traveling idle	Stopped idle	Total non-productive
1	329	0.204	0.208	0.197	0.298	0.997	0.000	0.000	0.001	0.002	0.003
2	524	0.480	0.474	0.317	0.474	1.747	0.070	0.022	0.103	0.060	0.253
3	595	0.536	0.521	0.349	0.521	1.926	0.229	0.003	0.581	0.261	1.074
4	600	0.522	0.542	0.363	0.542	1.969	0.241	0.081	1.156	0.553	2.031
5	582	0.502	0.526	0.352	0.526	1.914	0.316	0.054	1.931	0.784	3.086
-	-	-	-	-	-	-	-	-	-	-	-

its PMHS is as low as 25%. Recall that the best performance obtained with the base model (layout 1*6) was around 23% with a PCP of only 90%. In fact, the lead time of parts within the system with buffers appears to be longer (in some cases) than for the system without buffers, which again suggests the presence of overlap phenomena.

As stated above, transfer lines are typically systems that are very efficient at producing very few products. Given the number of machines that have been used so far, it can be said that their routing flexibility is very low, since they could only produce two types of products. The base model can process more than two as long as the routing is uni-directional. The FMS with buffers can process at least twice as many different types of parts.

VIII-10. SUMMARY

The results of the previous sections indicate that the measurement of flexibility is ambiguous and depends on several factors. Some typical FMS configurations were tested.

The first type of these systems was a unidirectional layout without interstation buffers. Three configurations were tested: a single loop, a double loop and a ladder layout, all with the same six machines and routings. These were simulated with three different routings. The single loop layout seems slightly superior basically because of the relatively low traveling load imposed on the AGVS. However, all systems exhibited blocking problems and relatively high idle time.

These three configurations were tested with bidirectional segments linking machines to one another. It was found that without some sophisticated anti-blocking control procedures, these systems did not really dominate the other systems which only included unidirectional segments.

Finally, interstation buffers were added to the base model. These systems appeared superior both in terms of volume and routing flexibility as their capacity is much higher and their capability to process different routings is at least twice that of the base model. The ladder system appeared to be slightly superior to the single loop layout for two reasons. First, its layout configuration provides less congestion than for the single loop layout. Secondly, for some routings, the traveling load imposed on the fleet of vehicles is less than for the single loop layout. In this case, when a relatively large fleet size of vehicles has to be used, the ladder FMS appears more flexible, both in terms of volume and routing flexibility, than the single loop layout (according to the specified definitions of flexibilities used in this research). However, for small fleet sizes, (one and two for this particular case) the single loop layout is just as good as the ladder layout. This is due to greater distances between machines in the ladder layout.

IX- CONCLUSION

This research has explored the problem of evaluating new manufacturing technologies, in particular material handling systems (AGVS) within FMS. It has done so by developing evaluation procedures and processes that attempt to grasp the far reaching implications of these technologies in terms of opportunity costs and economies of scope. In particular, measures or indices of the flexibilities generated by AGVS within FMS have been developed and ways of how to use these measures have been proposed. In particular, flexibility indices can be used in a multi-attribute framework where trade offs are present among flexibilities. They can be linked to opportunity costs incurred by the organization that invests in new manufacturing technologies where flexibility is paramount. It is likely that for each type of index, an opportunity cost can be inferred. Finally, these indices can be used in the analysis of FMS from a purely technical viewpoint.

Flexibility as a concept is complex and its operational definitions are not easily implemented, as each of them typically reflect only one aspect of the overall flexibility of a system. Flexibility encompasses many performance aspects of a production system. Two major aspects of flexibility were explored in this research. A first one is that a system can adapt to change in a turbulent environment. More specifically, it was argued that a system is more flexible if less resources are needed to fend off a given perturbation. The elasticity concept of flexibility relates an external or internal disturbance to the necessary modifications to counteract it. Other indices were related to efficiency and effectiveness of the MHS. In particular, the flexibility of an MHS could be construed as how close and how fast it could reach an ideal

MHS, as more resources are added to the current MHS. An index of such closeness has been devised. On the other hand, this index of flexibility, which essentially measures the lead time reduction capability of a system does, not measure another very significant aspect of a production system that can be related to flexibility; namely overlap, This is why it was concluded that the last index had to be used with another one which measures how close the FMS reaches its throughput capacity. In other words, increases in throughput does not always require lead time reduction.

These two fundamental aspects of flèxibility were related to volume flexibility and partially to routing flexibility. Volume flexibility seems to be a relatively easy type of flexibility to quantify. Routing flexibility is more difficult since it involves combinatorial aspects not easily grasped in an index. Simplifying assumptions were made during this research, so that routing flexibility could be linked to the product mix directly (that is, the n parameter). Finally, expansion flexibility is somewhat different as it is related to disruptions that are more substantial and have long term effects compared to the two other types.

The interdisciplinary aspect of flexibility was also emphasized in this work when multi-attribute models were used in one of the evaluation processes. Flexibility is a concept that is to be linked to technical , system, economic and strategic variables pertaining to an organization. This concept is therefore central to any evaluation procedure that involves FMS and their material handling systems. The notion of flexibility guides the choice of equipment, which technically generates the different types of flexibilities. Flexibility permits an assessment of the overall performance of a system when all these equipment items are put together within the design of FMS. Flexibility also guides the economic assessment about the likely opportunity costs reduction when the firm possesses the several flexibilities. Finally, flexibility is instrumental in reaching overall strategic goals where product differentiation and environmental uncertainty prevail.

Extensions of this research are proposed below and follow from the limitations of the evaluation process and the flexibility indices developed thus far. So far, FMS models studied have involved deterministic machine time parameters. Stochastic operations time is a natural extension of the current research, as flexibility indices should be involved with the probabilistic nature of manufacturing systems.

Another extension of this research is the use of flexibility indices that include dynamic aspects, such as transient responses, as opposed to steady state systems which were studied so far and for which the flexibility indices were developed. In particular, the problem of rerouting loads in a real time fashion is certainly a type of flexibility that could be studied. An important aspect of flexibility is how fast can a system recover from a disturbance. In other words, what is the length of the transient response between two steady states ? The shorter the transient behavior the more flexible is the system. This type of measure is likely to be of importance since turbulent environments will have the effect of generating several of these transient responses. At the limit, steady states may be the exception as an FMS deals mostly with transient responses.

Routing flexibility is a type of flexibility for which more research is needed, especially as it is related to other flexibilities. If the assumptions (concerning this type of flexibility) that were used in this research are relaxed, then other aspects such as alternative operation sets, machine scheduling, and vehicle routings must then be taken into consideration within a new framework that would include all these levels of flexibilities. Flexibility would therefore be synonymous to *variety* from a system viewpoint.

Unlocking procedures is another aspect of AGVS system that increases their efficiency, and therefore their (routing) flexibility. Several mechanisms can be devised so that the FMS does not lock. One of them is the use of interstation buffers. Other ones include look ahead capabilities and dynamic rerouting. The study of such mechanisms is another extension of this research.

The flexibility of MHS equipment mix is another natural extension to this research, as it may be advantageous for a firm to have more than one type of MHS. For instance, conveyors can be combined with AGV's to produce an overall FMS where relatively high volume parts are being processed in parallel wth low volume parts. Another example of such mix is with a system that uses several assembly lines simultaneously. In this case, AGV's bring loads to assembly lines which use conveyors to move these loads from station to station.

A critical aspect of the use of analytical techniques, in particular, network models, is their limitations. More research is needed so that their domain of application is better known. Moreover, the interface between these techniques and simulation needs to be improved, so that the outputs of the former may be used as parts of the inputs in the simulation phase. Another potential research avenue is the degree to which math-based techniques, such as network flows, measure economies of scope, which is a major characteristic of new manufacturing technologies such as FMS and CIMS.

The flexibility indices developed so far could be extended to other types of flexibilities pertaining to machines. Eventually, these indices could be integrated in the design process of FMS. A decision support systems would be useful in implementing these indices and the evaluation processes proposed in this research.

There is no doubt that flexibility plays a major role in the design and evaluation of modern manufacturing systems. Only a thorough analysis with respect to this aspect can really help in making the right decision concerning the investment in systems such as FMS and CIMS. Further studies are needed in devising detailed integrated evaluation procedures. This research has outlined what such processes could be and what kind of flexibility measures could be used in order to reach this objective.

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