WORKING PAPER

INTERACTIVE ANALYSIS OF FMS PRODUCTIVITY AND FLEXIBILITY

Jukka Ranta
Alexandre Alabian

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

FOREWORD

There are clear indications that the implementation process of flexible manufacturing systems (FMS) as well as of other CIM technologies is a key to their planned benefits and intended impacts. Apart from the many organizational and managerial issues during planning and implementation, also many techno-economic tradeoffs have to be made, such as flexibility vs. capacity, current needs vs. future potential, or short-term benefits vs. life-cycle costs and benefits. Basically the investment decision and systems selection is a multi-criteria problem.

This working paper formulates an FMS efficiency model and the multi-criteria FMS selection problem. An interactive decision aid is used to analyze FMS productivity, flexibility, to select the system and to understand the tradeoffs between conventional technologies and cellular systems.

Prof. F. Schmidt-Bleek
Program Leader
Technology, Economy, Society

SUMMARY

The paper presents a cost-efficiency model of a flexible manufacturing system (FMS) in order to analyze and make a tradeoff between flexibility, capacity, and to select a proper system. The efficiency model is based on the time sharing concept, where manufacturing time (machine resources) is allocated to different parts (batches). The allocation is dependent on the complexity and other features of different parts. A simple cost model is included, taking into account different cost factors, such as machine, tool, software, planning costs, and systems features. The model is implemented into a multi-objective programming system to make tradeoffs and analyze different alternatives. The system can be used in an interactive way, so that the decision maker can compare different feasible solutions, or in order to optimize different multi-criteria value functions. Relative performance indicators and different value functions have been included. A numerical example demonstrates the system properties. The model and the interactive system form the basis for understanding decision making on FMS investments as well as for analyzing which techno-economic factors have an impact on the benefits of FMS and company-level decision making.

INTERACTIVE ANALYSIS OF FMS PRODUCTIVITY AND FLEXIBILITY

J.Ranta, A.Alabyan

1. INTRODUCTION

Flexible manufacturing systems (FMS) are key technological tools to provide flexibility on the shop floor. Together with the other CIM technologies, they are thought to be technological driving forces of the current manufacturing changes. There are many benefits and goals attributed to FMS: the ability to make variations and customize products, to decrease delivery time, to decrease work-in-progress, to decrease capital costs, to improve quality, etc. However, FMS technologies are very complex and capital-intensive technologies. Realization of all those expected benefits necessitates a very careful design and implementation of the systems, starting from the assessment of the all-over business impact and ending with the concrete implementation of software systems.

The design and implementation problems of flexible manufacturing systems (FMS) can be regarded as a multilevel and multi-objective task. At the first stage the task is to solve the interaction between business strategy and different manufacturing concepts. On the second stage it is to find a proper architecture of the production system and relate it to the future needs of different production strategies. This is basically a task of balancing the needs for capacity and production variations, effected costs and benefits, and economic risks inside existing resource constraints set by technological alternatives. Finally there is the concrete refinement of the layout - selection of machines, devices and vendors as well as detailed selection of parts to be produced together with the control hierarchy and scheduling of the system. Then the final implementation and detailed technical design can be started.

During the different design stages there is a need to analyze and compare different alternatives against expected benefits and costs. Although there are many operation research models and simulation technologies for different design phases, in practice many heuristic approaches are used instead. This is especially true for the systems specification and layout design. Thus there is a need to improve design methods and their interactive features.

Sections 2 and 3 of this paper describe the design problem connected with the problem of FMS flexibility and productivity analysis. Section 4 presents a review of the existing approaches of FMS planning and analysis. A basic FMS model under consideration is formulated in Section 5. Section 6 is devoted to the mathematical setting of the multi-criteria problem connected with the FMS flexibility and productivity analysis. An approach to solve the set multi-criteria problem using the Feasible Domains evaluation technique is presented in Section 7. Interactive system and some programming aspects are discussed in Section 8. Section 9 presents the discussion and suggests further development of the model. Appendix A contains a numerical example of the FMS analysis, and Appendix B gives the definitions.

It is planned in the nearest future to show all the possibilities of the above approach as well as IFDES (Interactive Feasible Domain Evaluation System) on the basis of a case study for one of the real manufacturing enterprises and a concrete FMS.

2. THE CONCEPT OF FLEXIBILITY

Flexible manufacturing systems and production automation in general are capital-intensive technologies. In order to obtain advantages, these new manufacturing technologies and concepts require careful implementation and design of systems. In principle, one can say that successful applications and realized benefits depend more on the design and implementation and on the related social and managerial factors than on the technology itself. There are examples and conclusions that the planned benefits are usually not realized, the timetables are overdrawn, and the costs of the systems are much higher than originally planned. Moreover, many case studies refer to poor availability and to poor utilization rates of the realized systems. Again, these operational problems can often be related to design, social and managerial factors (Meredith, 1987a,b; Jaikumar, 1986; Martin, 1987; ECE 1986).

In any case, we may expect that the diffusion of these new technologies also depends highly on the above factors. Thus the main questions are: how to develop flexibility, what are the costs of the flexibility and what are the technological and organizational means to realize the flexibility. The goals to achieve flexibility and to make variations in an economic way relate to manufacturing strategies, and to business strategies in general. However, there are very few tools to evaluate different design alternatives and to integrate many -- sometimes contradictory -- goals. Therefore there exists a special need for developing decision-making aids and an investment evaluation methodology.

Usually economies of scope are referred to as the ability to make product variations in an economic way. More generally we can regard flexibility as the main result of successfully realized economies of scope. The concept of flexibility has many dimensions and reflects many goals of companies. Flexibility can be regarded as:

- an ability to make product variations
- an ability to have short delivery times
- an ability to cope with complexity
- an ability to change production volume and batch size

and thus satisfy different customer needs. This has to be done economically and with a view to high quality.

It is commonly considered that economies of scope and the ability to focus and differentiate are the main sources of the competitive advantages and strengths in many manufacturing industries. Moreover, economies of scope are also an important issue in commodity industries, e.g. in the paper and pulp industry and the chemical industry.

From the systems implementation point of view we can point out three main factors behind flexibility. First, the question refers to technological and organizational solutions in order to achieve a trade-off between production capacity and required product variations and, on the other hand, to guarantee the lowest possible life cycle costs (design, start up, operation). The second question refers to the risk of investment: how can we be prepared for the future market and product changes and still be flexible enough, or, in other words, how many resources should be allocated for short-term consideration only, and how much pre-design and pre-reserve change potential is needed for the coming market and product changes. The third question refers to designing the whole manufacturing structure: own production or subcontracting, and how to distribute the goods. These basic problems can usually be split up into the systems, which are guiding, planning and design process goals. As we will see later, these goals are usually conflicting with each other.

On the manufacturing level flexible manufacturing systems, and more generally CIM, are special tools and concepts which allow for an integration of different functions, such as product design, production planning and control, manufacturing control, and factory level transportation. Moreover, FMS and CIM usually offer solutions in production organizations, which lead to a decrease in capital costs, work in progress, inventories, delivery times, batch sizes and to an increase in the economic variety of products as well as in the quality of the products. Many goals related to the economies of scope are usually considered to be achieved only through these manufacturing measures. Although they are important and necessary tools to achieve flexibility, they alone are not satisfactory. The whole concept of the manufacturing logistic system has to be changed if we try to achieve the real benefits of economies of scope and flexibility. Usually we can describe these changes in the following way (see also Ranta et al., 1988b).

Design flexibility is needed to guarantee that specialized and customized versions of a product can be drawn up rapidly enough to achieve rapid tendering of offers and also to be able to make different versions of offers. Moreover, design flexibility also makes it possible to introduce product changes rapidly on the factory floor. In a broader sense, a part of the design flexibility is also the capability to plan production schedules and change them flexibly according to the changed needs. This guarantees rapid all-over delivery times and rapid confirmation of orders. Usually the realization of design flexibility requires changes in product design. A modular design is needed to grant possibilities of design alternatives and to implement flexible manufacturing.

Manufacturing flexibility means that the manufacturing process has a capability to make small batch sizes, to make variations and to have a short throughput time. Usually manufacturing flexibility corresponds to the common idea of flexibility and it is generally realized by using flexible manufacturing systems and flexible production automation. Of course, this is a necessary requirement for a flexible company.

A flexible raw material supply is needed to guarantee the flexibility of the whole manufacturing logistic chain. It is a common practice to have a flexible subcontracting network and just-in-time production for part supplies.

Finally, the distribution network also needs to be flexible and to allow for a reduction of the final product storages.

One can easily recognize that in order to decrease the total response time the most important phases are order processing, planning and product design, as well as distribution. On the other hand, the ability to make variations is mainly provided by the design, planning, and manufacturing systems, as well as by the subcontracting network. Complexity is provided mainly by planning and manufacturing. Volume flexibility and batch size flexibility are mainly related to the manufacturing and subcontracting network, but other functions are also essential.

One of the critical issues is thus how to provide manufacturing flexibility. We can split this concept into several subitems, such as (Son et al., 1987; Yilmaz et al., 1987; Stack, 1987; Gerwin, 1987):

- machine flexibility, which requires machines which have all the necessary properties: easy changeability of workpieces and tools. This requires the existence of enough pallets, fixtures, tool magazines, and the physical limitations of the machines must not inhibit changes;

- process flexibility, which requires processes that allow tooling of the part family in a mixed order. This requires machine flexibility as well as supporting planning flexibility;

- product flexibility, which requires an easy shift to a new product or a new part family; and

- production flexibility, which reflects the economic barriers to a change in production volume, in the routing of the workpieces, in tooling sequences etc.; usually it is also referred to as routing and sequencing flexibility or structural flexibility. In any case, it reflects the basic structural limitations of the system and it is related to the properties of the transportation system, warehousing system, interfacing system, systems control and software modularity.

Of course, it is possible to define the above concepts in greater detail and there are many different definitions, but these concepts should just give an insight before the economic issues of flexibility are considered.

It is very common that the first step toward flexibility is to provide design flexibility with a modular product design. This phase necessitates an investment in a design system or CAD. Manufacturing flexibility is realized by a manual system or, usually, by a very conventional manufacturing process. In any case, the design system provides the basic flexibility and decreases the total delivery time and gives possibilities to generate different variations and design choices in a rapid and cost-efficient way.

The second step also consists in building up manufacturing flexibility. In this phase a subcontracting network is also built up. The common solution is to increase the automation level of the manufacturing process by utilizing flexible manufacturing systems. This is a major investment and requires a lot of experience and knowledge. This is why the prerequisites for a successful implementation of FMS are a clear product strategy and relative strength created by a focus and differentiation. Flexible manufacturing can again decrease delivery times and even increase production capacity without loss of flexibility.

The above described strategy seems to be very common in the metal product industry and the workshop industry. The approach, of course, can be completely reversed: i.e., first to advance manufacturing and afterwards to develop support functions. In that case the basic goal is not to provide variations and flexibility, but rather to increase production capacity, improve quality, save capital and other resources. Flexibility can then be achieved rather as a side effect.

3. TECHNOLOGICAL AND COST FACTORS OF FLEXIBILITY

In this chapter the focus is on technical factors of manufacturing flexibility in the metal product industry. Thus the basic target is supposed to be a flexible manufacturing system. Furthermore, this system is supposed to contain NC-tools or machining centers, automatic transportation and warehouses of workpieces and tools as well as automatic tool and workpiece changing operations.

The design usually starts with the overall goals of the system. The reasons may be (see Shah, 1987; Ranta et al., 1988a,b):

- to increase product variations or product flexibility,
- to decrease throughput time and increase delivery flexibility,
- to save capital, e.g. by decreasing work in progress, decreasing storages, decreasing the amount of machinery, or by high availability of the systems,
- to improve quality,
- to increase production capacity.

Usually the systems design team has a general idea of the basic properties of the system as well as of the lay-out of the system. This is based on the known product properties and the required tooling functions. Based on this concept different alternatives are analyzed and evaluated and a cost-benefit analysis of the alternatives is made. This lays down the architecture of the system together with the basic control structure. Afterwards the detailed systems design begins, such as choosing machines, robots, etc., implementing the software, training of personnel.

The system concept has several goals and objectives, which can be contradictory to each other. To analyze different alternatives and to evaluate them with respect to the overall goals requires special methods, because there are a lot of interactions, and long-term effects must also be taken into account.

Usually the starting point is the need for a certain capacity. This is simply necessary to fulfill the required volume of production. Moreover, there might also be variations in the required volume of different products, as well as a request to take into account future changes in this volume. In small and medium size companies the increase of the production capacity can be the most important reason behind investment in a flexible manufacturing system. Thus the first characteristic of flexibility is volume flexibility: the need to have a certain amount of capacity and to vary the capacity for different products according to demand fluctuations.

Another important characteristic is the ability to make variations. This property is usually measured by the total amount of different parts, called the part family, which is needed for production. In general a greater part family means less production capacity. The part family is usually restricted by many technological as well as economic factors.

One further indicator to measure product variations and also the third characteristic of flexibility is the complexity of parts, or the amount of different surfaces, accuracy of parts and dimension of parts, which the system is able to make and which are needed for production. This concept of complexity is an important characteristic of flexibility. Usually it again holds that an increase in complexity will decrease the production volume. The more complex parts the system is able to produce, the larger the part family a system can basically have. The complexity of parts is also restricted by many technological and economic factors. In any case, an investment for complexity can be an investment for the future and will help to cope with the future market changes.

The fourth goal and at the same time the fourth characteristic of flexibility is the batch size. Of course, it is preferred to have a batch size as small as possible. But, again, the small batch size will decrease the production capacity and therefore there will be an optimum batch size, which is much higher than one. Theoretically, a small batch size will decrease total delivery time, which might be a goal as such, but the small batch size will lead to overheads because of tool changes, etc. This is why there is a need for a trade-off.

Each of the goals has its costs, of course. One of the aims of the design is to have a cost/benefit ratio as good as possible.

Usually we can find the following simple relationships:

1. Increase of part family

- will increase the need for machine flexibility as well as for process and production flexibility;
- will increase software costs, because more NC-programs are needed as well as more integration software;
- device or hardware costs will increase, because more pallets, fixtures, storage space, robot capacity are needed.

2. Increase of volume or capacity

- will mainly increase the need for production and process flexibility;
- will increase the time needed for batch changes;
- will increase hardware and machinery costs;
- will increase pallet and fixture costs;
- will increase auxiliary device costs, because of increased demand for resources;
- will increase technical non-availability time;
- will increase software costs, because of more complex systems control.

3. Increase of complexity

- will increase mainly the need for machine and product flexibility;
- will increase software costs, because of more complex part programs and a more complex systems control and integration;
- will increase tool, pallet and fixture costs;

- will increase technical non-availability time.

4. Decrease of batch size

- will increase the need for process and production flexibility;
- will increase software costs, because of a more complex systems control;
- will increase auxiliary device costs, because most probably more (and more complex) pallets are needed.

Moreover, also other goals, such as short delivery time and decreased inventories, reflect -- through the previous basic categories -- increasing implementation costs. There is also evidence in practice that the increased capacity of systems and the increased complexity will increase the systems costs/machining unit in a stepwise manner (see Sheinin et al. 1987, 1988; Tchijov et al., 1988). This is due to the need for more efficient machinery when a certain level of complexity is reached. And this is, basically, due to the transportation and warehousing systems and systems control. In small size systems it is enough to have a compact type of material handling system, such as a conveyor, and simple systems control based on programmable logic. When the complexity increases, a more sophisticated material handling system is needed, such as automated guided vehicles, and the systems control has to be based on computers, distributed data bases and integrating communication systems. These changes in systems complexity tend to change in the stepwise manner (for more detail see Ranta, 1988).

Apart from the basic systems costs related to technology, there are other important cost factors concerning organizational and management issues. The complex and expensive systems are usually critical to the whole business strategy and therefore special attention has to be paid to the long-term effects. Moreover, the increased complexity requires highly skilled personnel to operate the system and to guarantee high availability and utilization rates. Therefore special emphasis has to be put on the training, both on content and methods, and on the evaluation of its effects on the life cycle costs of the system.

Thus we can conclude that, apart from the short-term design problem, there are long-term trade-off problems.

The first of them is to minimize the life cycle costs of the system. This is a trade-off problem between high availability and short-term implementation and training costs. The second is designing for future flexibility, which is basically an economic risk problem and a plant or company strategy problem.

Many of the above factors are related to the current technology and its economic capabilities. Pallets and fixtures are still expensive and they are main obstacles to machine and process flexibility. General-purpose -- but economic -- pallets and fixtures are still to be developed. The possibilities to make prismatic and rotational parts at the same manufacturing center are growing, but a real general-purpose machine and thus a remarkable increase of machine flexibility as well as process flexibility is still beyond our present economic capabilities. Production flexibility as well as structural flexibility is dependent on software issues. A modular system software as well as a proper interface system can guarantee systems extendability in the future. An open communication system as well as the use of a common communication protocol will help to increase production flexibility. A modular software design and standardization of systems software can, in general, decrease tailoring and application design costs. In any case, software engineering is a key issue when we try to guarantee the availability of systems and their high reliability. An increasing amount of functions will be controlled or realized by software (see Ranta, 1988).

The above design problem can be summarized as shown in Table 1.

Table 1. Cross-impact of goals and technical features

Features	Impacts				
	Goal	Flexibility	Volume	Availability	Cost
Part family	Large	+ +	-	+ / -	+
Batch size	Small	+ +	- -	-	+
Complexity	High	+ +	- -	- -	+ +
Capacity	High	-	+ +	+ / -	+

(+ increasing, - decreasing)

Thus the problem is to find a proper technical solution, such as layout, systems configuration, machines, tools, etc., which is satisfactory (feasible) in terms of features and impacts, and which has a minimal economic risk.

In order to analyze the problem of flexibility and productivity of FMS, let us first try to formulate the place of this research in the overall scheme of FMS planning and analysis.

4. BASIC APPROACHES FOR FMS PLANNING AND ANALYSIS (OVERVIEW)

There are several levels of activities connected with the FMS planning and analysis process. Suppose the problem is to consider the development of FMS for the given purposes of production. Both technical and organizational problems may be faced during the installation of FMS. Obviously, the solution of technical problems such as chip removal, swarf clearance and retrieval, design and control of fixtures, tool management, etc. is a prerequisite for success. However, the successful implementation of an FMS will depend strongly on the selection of efficient planning and control policies. In setting up an FMS one is confronted with the increased capabilities of modern equipment, but, at the same time, with increased constraints and demands. It is clear that a single analytical model or a single practical approach can not solve all planning problems.

A hierarchical multilevel framework can be considered for FMS planning and analysis (see Figure 1), each level having its own subject of study, inputs, outputs and methods of research. Some reviews of the existing mathematical methods and useful algorithms can be found elsewhere (see, for example, Kusiak, 1986; Van Loovern et al., 1986; Kalcunte et al., 1986). The overall procedure of FMS planning and analysis can be divided into 5 levels.

Level 1, strategic planning, is the responsibility of top management and deals with long-term decision making and strategic decisions concerning the choice of machines, tools, the production family to be used in the enterprize, the economic evaluation of future manufacturing features, and so on. An FMS should be perfectly justified at this level because:

- the lead time required to install an FMS may be fairly long;
- a significant amount of investments must be committed;
- a high degree of risk is involved.

These strategic decisions are usually made with the help of FMS market analyses and of analyses of available equipment, financial, organizational and some other resources. Methods of economic estimations, statistics and expert analyses are widely used for these purposes.

On the second level the chosen equipment is being grouped to divide the overall production planning problems into sub-problems. Grouping machines into Flexible Manufacturing Cells is considered to be a logical division according to the current planning needs. FMS parts can be aggregated, subject to similar requirements on tools, fixtures, pallets, robot grippers, machines. Methods of cluster analysis, binary comparison using binary matrices, and some elements of mathematical programming are used to solve this problem. On the basis of this analysis several variants of FMS configuration, production volumes for all parts to be produced, some time and cost limits, as well as a set of possible batch sizes are expected to be formulated.

Level 3 is mainly devoted to the problems of machine loading and batch-sizing (lot-sizing). These problems are closely connected with the FMS flexibility analysis. At the same time productivity parameters are being estimated (time and cost factors). Parameters of chosen machines and features of parts, estimated on the previous level, serve as an input for this research. Mathematical programming methods, algorithms and computer programs are mostly useful for this purpose. Concrete methods depend mainly on the complexity of the FMS model under consideration and may include different linear and nonlinear programming algorithms. If so-called risk factors are taken into account (such as failures of equipment or unexpected rapid changes in part family or other FMS parameters), the methods and algorithms of stochastic programming seem to be relevant.

Level 4, operational planning, is connected with the problems of optimal routing, equipment allocation, inventory estimation, materials handling system scheduling, etc. Queuing networks can be used here as an aid to solve these problems. Other approaches that are known in the literature use the graph theory and Markov's processes approximations. The estimates of machine loading, the values of batch sizes for parts, and the time and cost requirements obtained on the previous level serve as an input for an operational analysis.

Finally, the 5th level is an FMS simulation to verify all estimates obtained for the FMS before its implementation in the real production

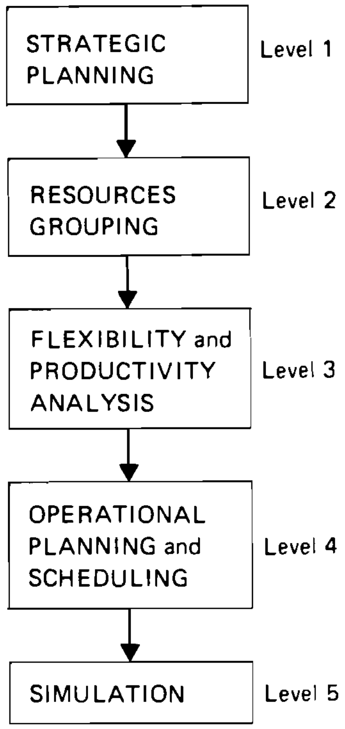


Figure 1. General scheme of FMS planning and analysis.

system. Simulation analysis is an indispensible tool to mimic the detailed operation of a system by means of a computer program that effectively steps through each event that can occur in the system. Simulation analysis can be performed at different levels of sophistication and therefore with varying degrees of accuracy and credibility. In FMS simulation it is used to test the layout of the system (screening), and to study the effects of different control strategies, scheduling priority rules, breakdown scenarios and maintenance schemes (releasing and dispatching). To simulate an FMS one can use a general purpose simulation language or a specific FMS simulator. Several general purpose languages are used in FMS modelling: e.g. GPSS, GASP, SIMSCRIPT, SLAM and, on their basis, other specific packages were developed for FMS simulation. They usually have a modular structure to simplify model building and data imputing.

Our effort here was aimed at analyzing the 3-d level problem of flexibility and productivity analysis, supposing that the input data needed for this analysis is given from the previous levels. The most difficult and important problem in this connection is the problem of having a reliable system model, because the success of the given analysis depends strongly on its choice. The next chapter is devoted to FMS modelling.

5. FMS MODEL

In modelling FMS, the critical resource is supposed to be time: each machine can operate for a fixed amount of hours annually. This time consists of the actual tooling time, the overhead times, such as tool and batch changing, and technological disturbances. All these times are influenced by complexity of parts, batch sizes, part family, etc. E.g., the more complex parts need more tooling time and small batch sizes might lead to longer overheads and to higher disturbance risks.

The second critical resource is money or the amount of capital needed for investments. The time resource and the investments are interrelated and often contradictory parameters. More efficient machines are obviously more expensive, but can also provide a more effective tooling time.

Thus the systems implementation problem is subjected to time and capital constraints. The general problem of systems design is to provide the necessary production volume or capacity within given time and cost limits, but at the same time:

- have as large part family as possible,
- have as small batch size as possible,
- produce as complex parts as possible.

All these goals can not be achieved optimally because of the limited resources and the multi-criteria nature of the problem. But there are many alternative solutions. The model itself has to provide these solutions and the DM (designer) has to make the final decision on the basis of these alternatives, trying to increase flexibility while maintaining sufficient production features. In this case the modelling effort should be applied to expressing relationships between parameters of FMS flexibility and productivity.

Suppose an FMS is to manufacture a part family consisting of N parts. Each i-th part has its own batch size bi and number of batches vi in the output product. The annual production volume constitutes V:

$$V = \sum_i Vi = \sum_i vi \times bi \qquad (1)$$

Each part has its complexity factor Gi that characterizes the complexity of its treatment by a machine. This factor can be measured depending on the form of a part, precision and other factors. For example, for simplicity it can be measured as a number of different surfaces of the part. This measure will be used below.

All these parts are to be treated by several machines. Parameter Mj denotes their type. Each machine can use some tools that are denoted by parameter Ljk, where k is the number of tools for the j-th machine.

The output figures that will be considered here are T, time factor, and K, cost factor. The problem is to organize a procedure of decision making which minimizes these two factors for given machines, tools and parts. It is well known that these two factors are contradictory because, by trying to decrease the production time, it is usually necessary to increase investment to the FMS by using more machines or more complicated and expensive machines. This is why we use in our approach an interactive procedure and an interactive system for decision making, based on the approaches of multicriteria problem solution.

Let us formulate the FMS model to be considered in terms of time and costs of production.

Time

Denote Tij - time needed for the machining of part i at machine j. It holds:

$$Tij = Tij + tij ,$$

where Tij is the actual tooling time, and tij is the overhead time (changing, waiting, checking, repairing, etc.).

The time factor for the j-th machine then holds:

$$Tjmin <= \sum_i (Tij + tij) \times vi \times bi <= Tjmax. \qquad (2)$$

Denote Td - technical non-availability time, Tbi - batch change time, Tmax - theoretical annual time available (maximum time for the production of the whole set of parts), Tmin - required minimum time of active production (it should not be too low to avoid overloading of one part of machines and idleness of the other).

Tjmax for all machines can be, e.g., one year.

For the whole line:

$$T\Sigma\text{min} <= \sum_j \sum_i (Tij + tij) \times vi \times bi + \sum_j \sum_i (Tbij \times vi) + Td <= T\Sigma\text{max} \quad (3)$$

where $T\Sigma\text{min} = m \times T\text{min}$, $T\Sigma\text{max} = m \times T\text{max}$,
m - number of machines in the FMS.

If Tbij are equal for all machines, then (3) will give:

$$\hat{T}\text{min} <= \sum_j \sum_i (Tij + tij) \times vi \times bi + m \times \sum_i (Tbi \times vi) + Td <= \hat{T}\text{max} \quad (3a)$$

where $Td = \sum_j Tdj + Ts$,

where Tdj is a machine disturbance and Ts is the systems level disturbance time.

The factor Td is dependent on some design factors:

$$Td = \sum_i TGdi \times Gi + \sum_i \overset{b}{Tdi} \times vi + \overset{s}{Td} \times SS - \overset{pl}{Td} \times PL, \quad (4)$$

including correspondingly complexity factor, batch change factor, software size factor and personnel training factor.

The disturbance formula is an empirical formula based on findings from real cases (see Kuivanen et al., 1988; Lakso, 1988; Norros et al., 1988):

- The major part of the disturbances are due to two basic problems: software errors and interfacing problems, and mechanical problems related to fixtures, tool changers, etc. Therefore we can put forward a hypothesis that the systems disturbances are correlated to the size of the systems software, the complexity of parts (more complicated fixtures, etc., and more interfaces) and batch changes (interfacing).

- There are indicators that systems training and extended training of operators improve the utilization rate and availability of the system.

Cost

Cost, K, of FMS production consists of machine costs, Mc, tool costs, Lc, parts pallet costs, Pc, software costs, Sc, transport costs, Tc, and some other related costs, Oc. It holds:

$$K = Mc + Lc + Pc + Sc + Oc + Tc, \tag{5}$$

where:

$$Mc = \sum_{j} M_{Ej} \times Ej, \tag{6}$$

which are considered here to be direct investment costs.

Parameter Ej in expression (6) defines the efficiency of machines. It can be evaluated by:

$$Ej = \sum_{i} E^{m}_{ij} \times vi \times bi \times (Tij + tij), \tag{7}$$

where E^{m}_{ij} is the efficiency coefficient:

$$Lc = \sum_{k} Lkj \times R_{Lj} + \sum_{i} Gi \times R_{Gi}, \tag{8}$$

$$Pc = \sum_{i} P_{Gi} \times Gi + \sum_{i} Pbi \times bi + \sum_{i} Pvi \times vi, \tag{9}$$

$$Sc = \sum_{i} S_{Gi} \times Gi + \sum_{i} S^{*}vi + \sum_{i} Svi \times vi + \sum_{i} S_{Li} \times L$$

$$+ \sum_{j} S_{Ej} \times Ej. \tag{10}$$

The first member in (10) characterizes the software complexity factor, the second the capacity, the third the batch size factor, the forth the tools management, and the fifth the efficiency.

This formula is again an empirical formula, but according to case studies it is fair to make a hypothesis that software costs are related to NC-programs, scheduling and communication algorithms, and to the amount of interfaces needed; and, finally training costs are simply related to total training hours.

The internal transportation costs, Tc, including transportation devices and storages, are as follows:

$$Tc = T^{*} \times V + \sum_{i} Ti \times Gi + \sum_{i} Tvi \times vi \qquad (11)$$

which are depending on the capacity of the system, the complexity of the parts, and the number of the parts.

$$Oc = O^{*} \times PL,$$

where Oc characterizes the training of the personnel.

In practice the cost also have upper and lower limits, Kmax and Kmin, where Kmax can be maximum possible investment, while Kmin is some kind of starting capital (for example cost of equipment and salary of workers):

$$Kmin \leq K \leq Kmax$$

6. SETTING THE PROBLEM

As introduced in the previous chapters, two basic concepts of FMS are considered here: flexibility characterizing the ability to rapidly react to different changes in production specification, and productivity that reflects output features of FMS. The problem of the analysis of these two FMS features is considered here.

Using the above model it is possible to make different kinds of investigations in the field of FMS flexibility and productivity. Summarizing the above considerations, parameters that characterize flexibility and are included into the model are:

- volume, v,
- part family (number of parts to be produced), n,
- complexity of parts, Gi,
- batch size of the parts, bi.

Productivity, in turn, is characterized by volumes of production for all parts Vi, time factors, Tj, $T\Sigma$, and cost of production, K. The average throughput time can be calculated from the production times.

The subject of the analysis is the combination Machines-Tools (MT) that comprise FMS and layouts. In principle different combinations of MT can be chosen, each having its advantages and shortcomings in terms of flexibility and productivity.

The aim of the research is to analyze how parameters of flexibility influence FMS productivity for the given MT combination. The overall procedure of FMS analysis is divided into some stages. First it is necessary to choose a set of MT combinations that should be analyzed. Then different scenarios are to be formulated for each MT combination (for example, various changes in values of batch sizes, different part families with different values of part complexities, etc.). At the next stage system productivity factors are analyzed for each scenario under consideration. Productivity analysis can be formulated as follows. Each discrete alternative comprising scenarios (in terms of different sets of parts, batches and complexity factors) determines the parameters of the above described model of FMS. Volumes of production of all parts Vi serve as independent variables. Output criteria are Tj, TΣ and K. As it usually occurs in practice of real manufacturing systems, all these parameters have their own limits as lower and upper levels for production volumes, time and cost limitations. It should be noted, for example, that times Tj should have very strict lower limits, Tjmin, in order to avoid a situation where some machines are overloaded, while others have big reserves in capacities. Limits for the system productivity parameters can be called Feasible Domains of variables and criteria under consideration. The problem is to find such values of variables (inside their Feasible Domains) that correspond to the feasible values of the system criteria. In other words, for the above situation it is recommended not to optimize the system criteria, but to guarantee their satisfactory values with reference to their Feasible Domains.

Another problem arises when one deals with the manufacturing system that relates to the process of the real-life changes in system variables (or parameters) that cause the corresponding changes in the values of the criteria. If the solution obtained includes values of criteria not far from the given limits (boundaries of Feasible Domains), these limits can be easily violated due to these changes and the FMS productivity will fail to remain satisfactory. To avoid this obstacle it is recommended that the above solution should have values of criteria as close to the center of the Feasible Domains (average between lower and upper levels of criteria) as possible. This will guarantee more degrees of freedom for the FMS manager to change system parameters or volumes of production without undesirable changes in system productivity and to make the system more flexible.

Suppose the problem is to analyze Time and Cost factors for the given FMS. The total volumes of all i parts production are set as lower and upper values (Vimin, Vimax). Available machines and tools are known. Upper and lower levels of T and K are also given (Tmin, Tmax, Kmin, Kmax). The aim is to analyze different scenarios for the given FMS and investigate which values of Time and Cost factors can be obtained within the given limits. For each separate scenario the volumes of production Vi serve as independent variables in the expressions for Tj, TΣ and K. All other parameters in expressions (2 - 12) are considered to be given, referring to the concrete scenarios.

All the described expressions of which the system model consists can be combined into one set. Time terms (expressions (2,3,4)) can be rewritten in the form:

$$Tj\text{min} <= \sum_{i} \tilde{T}ij \; x \; vi <= Tj\text{max}, \qquad (12)$$

$$T\Sigma\text{min} <= \sum_{i} \tilde{T}_{\Sigma ij} \; x \; vi + B <= T\Sigma\text{max}, \qquad (13)$$

where B is the sum of all constant members of the time terms, and coefficients A_{ij} and B_{ij} generalize all other members in (2) and (3) related to variables v_i.

The cost terms can be expressed in the form:

$$K_{min} <= \sum_{i} \tilde{K}_i \times v_i + D <= K_{max}. \tag{14}$$

These three systems of inequalities can be combined into one system:

$$C_{smin} \leq \sum_{i} A_s \times X_{is} + A_{s0} \leq C_{smax}, \quad \text{or} \tag{15}$$

$$C^*_{smin} \leq \sum_{i} A_s \times X_{is} \leq C^*_{smax} \tag{15a}$$

where $s = 1 \ldots m+2$, $C_{smin} = T_{jmin}$, $C_{smax} = T_{jmax}$, $A_{is} = \tilde{T}_{is}$, $A_{s0} = 0$ for $j = 1 \ldots m$, $C_{smin} = T_{min}$, $C_{smax} = T_{max}$, $A_{is} = \tilde{T}_{\Sigma ij}$, $A_{s0} = B$ for $s = m+1$, $C_{smin} = K_{min}$, $C_{smax} = K_{max}$, $A_{is} = \tilde{K}_{ij}$, $A_{s0} = D$ for $s = m+2$, $C^*_{smin} = C_{smin} - A_{so}$, $C^*_{smax} = C_{smax} - A_{so}$ for $s = 1 \ldots m+2$.

The design problem for each scenario is to find values of v_i such that expression (15) is satisfied. This will allow to obtain satisfying output values of the time and cost terms for the given FMS. At the same time, as we have upper and lower limits but are not trying to find one optimal solution, we have enough reserves to obtain the satisfactory solution for the different parts, batches, machines and tools under consideration. In order to reach some degrees of freedom, taking into account possible real-life changes in FMS parameters and production conditions, it would be better to have a solution which is closer to the centers of the intervals between maximum and minimum values of the criteria functions.

As an output of this procedure there will be values of T_j, T_Σ, and K for each MT combination and for each item of the scenarios under consideration. Further analyzing the results of the calculation for all scenarios under consideration, the decision maker will be able to choose the best MT combination with maximum flexibility and satisfactory productivity.

Bearing in mind that the described procedure can not be carried out without the help of the computer, a special approach was implemented. It is described in the following section.

7. APPROACH

One of the most important problems arising during the design process of a complex system with the given model is usually the problem of obtaining a structure and parameters ensuring best performance.

The systems design is often carried out by computer optimization which assumes the minimization (or maximization) of a chosen criteria function. However, in technological, social, economic and other complex systems we often face a multi-criteria situation due to numerous requirements and conditions imposed on the indices of their quality. In this connection approaches that use interactive procedures and systems are most promising (see Nakayama et al., 1984; Grauer et al., 1984; Nakayama, 1985; Larichev 1979; Decision Support..., 1982; Processes and tools..., 1983; Multiple criteria, 1985; Alabyan et al., 1986). The main problem in this connection is to provide the best use of the strong points of the abilities of men and computers. Useful approaches have been developed using ideas of satisfying systems (Simon, 1972) instead of the optimal systems. These approaches give more degrees of freedom to the DM and are useful in many practical applications.

An Interactive Feasible Domain Evaluation System (IFDES) was worked out to cope with multi-criteria problems within the given system model. It is based on the concept of providing satisfying levels for each separate criteria function, evaluating the solution to see if it suits these levels, and keeping the satisfying levels up in spite of variable changes. Its detailed description can be found in Alabyan et al. (1986). Values of all criteria functions under consideration that lie inside the satisfying levels form domains in the space of criteria. These domains are called here Feasible Domains of criteria.

An attempt has been made here to use IFDES as a tool to cope with complex multi-criteria problems arising in the process of the FMS flexibility and productivity analysis.

The procedure of obtaining feasible levels for all criteria functions by the computerized choice of systems variables is called here a design procedure.

Denote X = (X1, X2,...Xn) - a set of systems variables, and C = (C1, C2, ...Cn) - a set of criteria functions. Note that the values of the criteria functions can be calculated by given values of variables:

$$C = C(X). \qquad (16)$$

(Equations (1) representing the system model in general can be linear or nonlinear).

If equations (16) are linear:

$$C = A \times X, \qquad (17)$$

where A is a (m x n) matrix, C is a m-dimension vector and X is a n-dimension vector.

Constraints are imposed on the values of all criteria functions:

$$Cj \in Fj, \qquad j = 1, 2, .. m \qquad (18)$$

and on the values of all systems variables :

$$Xi \in Mi, \quad i = 1, 2, .. n. \qquad (19)$$

Denote: F - Feasible Domain of C, M - Feasible Domain of X, Mc - mapping of M on the space Rc of criteria functions, S - general Feasible Domain of solution (intersection of F and Mc in Rc space). The aim is to find values X^* such that (18) and (17) hold true, and to maintain this situation for the whole set of changes of systems variables that can take place during the period of system observation. Coefficients Aij of matrix A are considered systems parameters.

Two cases of locations of F and Mc can be considered (see Figure 2):

A) Mc and F have an intersection and S is non-zero. B) F and Mc have no intersection and the solution can not be found due to the very tight constraints of Mi or Fj for the given set of system parameters.

Feasible Domains M and F can be expressed in the form of constraints:

$$Xmin <= X <= Xmax \text{ and} \qquad (20)$$

$$Cmin <= C <= Cmax \qquad (21)$$

representing lower and upper feasible values of X and C, where Xmin, Xmax, Cmin, Cmax are numbers.

Consider a system of 2n + 2m constraints constructed from (17), (20) and (21):

$$\begin{cases} X <= Xmax \\ -X <= -\ Xmin \\ A \times X <= Cmax \\ -\ A \times X <= -\ Cmax \end{cases} \qquad (22)$$

If (22) holds true, then the solution exists. IFDES has a special interactive procedure to modify the initial values of systems constraints or even parameters of the system (coefficients of matrix A) to obtain the

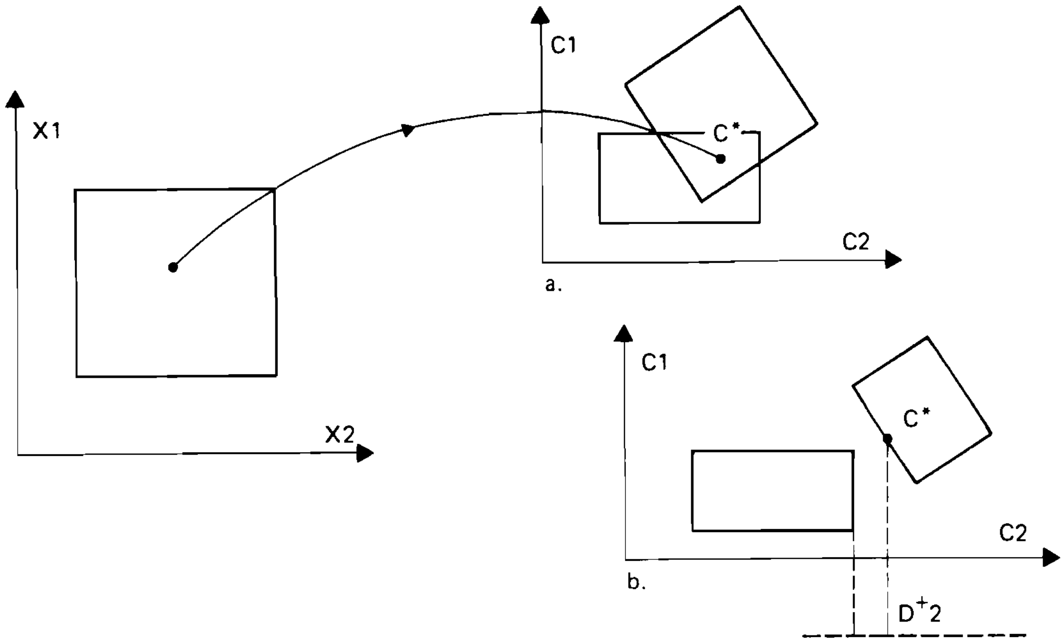


Figure 2. Two cases of interlocation of Feasible Domains for C and X.

solution of the design problem. We consider any solution satisfactory if it lies inside the Feasible Domain. The design procedure is formulated below.

With the help of experts the DM initially sets constraints on the basis of a preliminary information (upper and lower levels) for Xi and Cj and formulates the system model (in our case parameters of FMS and equations for the calculation of Time and Cost factors). All this information is introduced into a computer. On the basis of this real data a specialized calculator computes coefficients of matrix A and upper and lower levels for system variables X and criteria C to be loaded to IFDES. Then a computer provides such values of Xi (inside Mi) that satisfy the corresponding values of all Cj (22). As soon as this is done and any current point C* is inside S, the design procedure is over and the solution consists of corresponding components of X*. In the same manner the design procedure can be applied to another set of initial data.

The computational algorithms that lead the system to Feasible Domain S are called here Hitting Algorithms. There could be different Hitting Algorithms which are able solve this problem. Two Hitting Algorithms were chosen for IFDES: one using Random Search and the other using an LP-algorithm. If the system model is linear, the LP-algorithm is preferable, while the Random Search algorithm can solve the problem in a nonlinear case.

There are two types of deviations calculated for the end of the design process: D+j and D-j that are being calculated for both Hitting Algorithms (Figure 2b). If the solution is not found, these deviations (or at least some of them) are non-zero. Their values show which boundaries of C are usually mandatory for the success of the design procedure. If the solution has not been obtained by the Hitting Algorithm, the user analyzes if it is possible to improve the situation by changing the boundaries of the Feasible Domains for Cj and by restarting the Hitting Algorithm. There could be a case in which all reasonable adjustments of the Feasible Domains for criteria C (upper and lower levels) do not help.

The analysis of the values of coefficients in matrixes [A] and [AX] that are presented by IFDES to the user shows which Xi or Aij make the most valuable contribution to the calculated values of those Cj that have not been led to their Feasible Domains (Figure 3). First, the user tries to change the Feasible Domains for X (upper and lower levels), restarting the Hitting Algorithm each time, and if this does not help he should change the parameters of the system (coefficients of matrix A).

To illustrate the approach, consider a two-dimensional case (i=2 and j=2). Suppose the solution of the design problem was not obtained. The Hitting Algorithm found point C* that is mostly close to the solution. The calculated values for D+j and D-j and the rows of matrices [A] and [AX] for a two-dimensional example are presented in Figure 3. As one can see, the value of D+2 is non-zero. So a first attempt should be made to increase the value of constraint Cup2 and to try the hitting again. Let's suppose this did not help and the value of D+2 is again non-zero and it is not possible from the point of view of the DM to increase Cup2 any more. Observing the rows of matrices A and [AX] the user notices that the values of A21X1 and A22X2, that make their contribution to the calculation of C2, are rather big. Analyzing the values of coefficients A2j, one can draw the conclusion that, if the lower constraints for X1 and X2 are decreased, it is probably possible to find the lower values for C2. If the DM agrees to do so, we try the Hitting Algorithm again. If he does not, or if this is again not sufficient, it is recommended to change systems parameters, i.e. to decrease

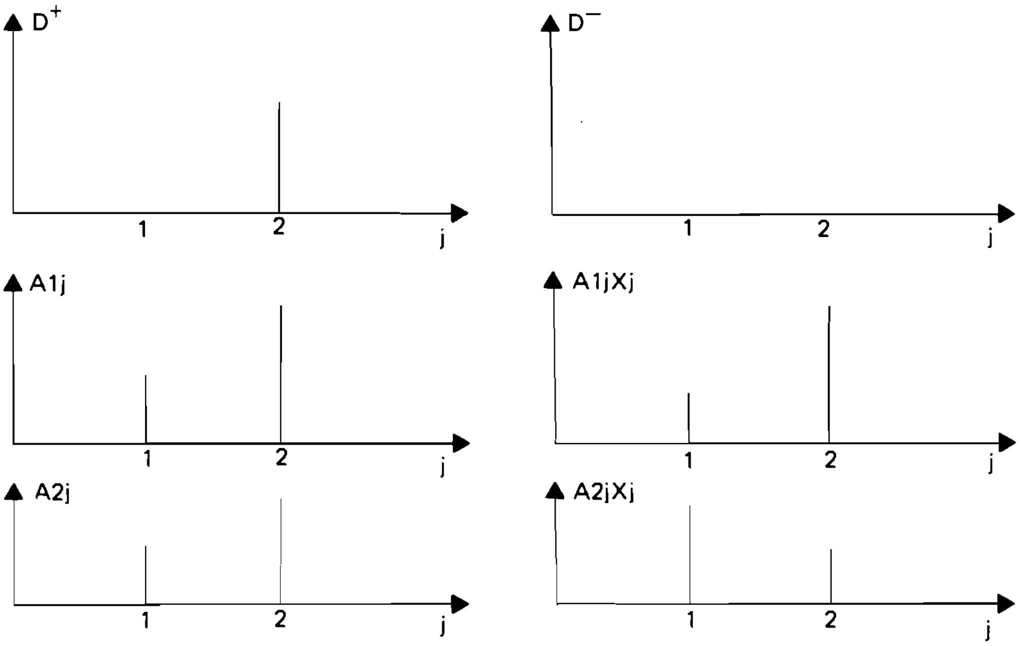


Figure 3. Histograms of values of D, Aij and Aij·Xj.

the values of A2j, because for the initial model and coefficients Aij the solution does not exist at all.

This interactive procedure involving the DM and the computer makes it possible to guarantee the convergence of the design procedure.

In our case Tj, TΣ and K serve as criteria, while vi serve as systems variables (Xi). The system model is expressed by the general expression (15) in terms of the IFDES matrix A (see (17)). The coefficients of matrix A for IFDES are calculated by given real parameters of the FMS under consideration (see the above FMS model under consideration) with a specialized calculator.

Another stage of the multi-criteria analysis of a system is to investigate how changes in systems variables, that may take place during system "life", can effect the satisfactory solution found. In fact, it can not be expected that real life will not make changes in the system under investigation. Many different events can happen that lead to the modification of the system parameters, of the values of system variables and of the upper and lower limits for the values of the criteria. This, in turn, can change the system performance, and the boundaries of the Feasible Domains of X and C can be violated. The DM would usually like to analyze if these changes will, in turn, change the given conditions for the satisfactory system performance. IFDES presents the possibility to insert new expected values for system variables or other changes into the system model (around the basic solution) in order to guarantee that in the future the behavior of the system remains satisfactory. If, for same cases, values of criteria are outside the Feasible Domains, the design procedure should be repeated. To guarantee more viability for the system the Hitting Algorithms are in this case constructed in such a way that we obtain the solution that corresponds to the values of the criteria nearest to the center of the Feasible Domain for C. This allows for a satisfactory preservation of the values of C in spite of some of the expected or unexpected changes in system variables Xi, parameters Aij, or boundaries of Feasible Domains for X and C.

In terms of our problem of the analysis of FMS those changes can take place in the volumes of production, batch sizes, investments, time factors, implementation of new machines with higher productivity, etc.

It should be pointed out that for different types of models (linear, non-linear, stochastic) different Hitting Algorithms can be incorporated into the design procedure that leads the system model to the solution with the set constraints on C and X (Feasible Domains). Here, in this paper, we consider the linear model of FMS and use the LP Hitting Algorithm. The Interactive Feasible Domain Evaluation System is constructed in such a way that it is not a very hard task to adjoin different available Hitting Algorithms. The only problem is to reformulate them to fit the concept of constraints in the form of expressions (20) and (21).

The design process for the linear model is formulated below.

Denote C^{o}_{j} - center of Feasible Domain for C_j:

$$C^{o}_{j} = | C_{j\,max} - C_{j\,min} | / 2.$$

Set the problem

$$\max_{j=\overline{1,m}} \left| C_j(x) - C^o_j \right| \rightarrow \min \tag{23}$$

Taking into account different dimensions of $C_j(x)$, we can normalize expression (23)

$$\max_{j=\overline{1,m}} \left| \frac{C_j(x) - C^o_j}{C^o_j} \right| \rightarrow \min \tag{24}$$

Let us introduce a new variable y such that

$$\frac{C_j(x) - C^o_j}{C^o_j} \le y, \quad j = 1,\ldots,m$$

$$\text{and} \tag{25}$$

$$\frac{C^o_j - C_j(x)}{C^o_j} \le y, \quad j = 1,\ldots,m$$

This means that

$$y \ge \max_{j=\overline{1,m}} \left| \frac{C_j(x) - C^o_j}{C^o_j} \right| \tag{26}$$

and the LP problem is as follows

$$y \rightarrow \min \tag{27}$$

subject to (22) and (25).

8. INTERACTIVE SYSTEM AND PROGRAMMING ASPECTS

The IFDES structure is shown in Figure 4. It was developed for the IBM PC compatible computers. IFDES software consists of several packages: a) an interface program, b) computational programs realizing Hitting Algorithms (LP and Random Search), c) a program simulating the system model, d) a

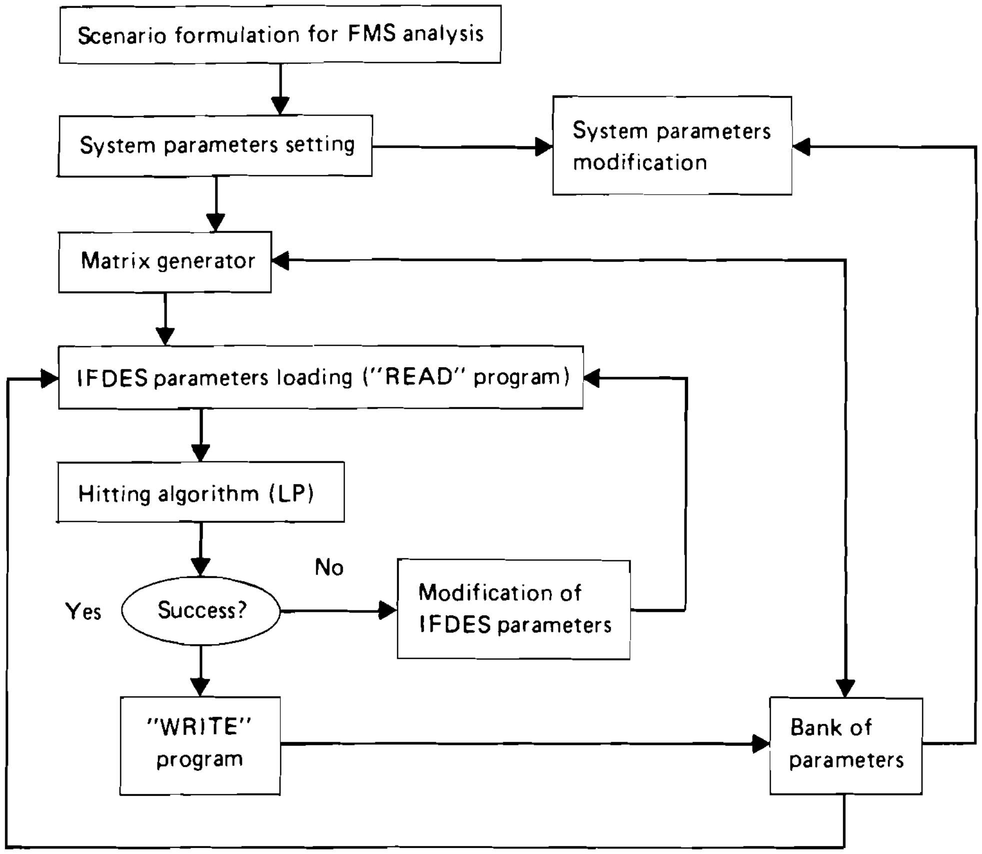


Figure 4. Decision support system structure.

program for calculation of IFDES parameters by given values of the real system model (matrix generator), e) the "READ" program to load different sets of IFDES parameters stored in the data bank, f) the "WRITE" program, to transfer calculated results and IFDES parameters to the data bank. The data bank is a number of ASCII files each of them containing different sets of IFDES parameters provided by calculator or imported from IFDES.

The software package Field Manager was developed to provide a flexible interactive interface between a user and an applied computational program (see Mazourik, 1988). It makes it possible to represent all necessary information on the screen during the computational process. Any of the program variables or constants can be located in several Windows each consisting of Fields.

The Linear Programming Hitting Algorithm based on the simplex method was worked out in the Computing Centre of the USSR Academy of Sciences. For the purpose of its usage in IFDES it was slightly modified. The parameter to be minimized by this algorithm is the radius-vector connecting the current value of C and the center of Feasible Domain F for criteria C. So it tries to find the solution nearest to this center. The Lp algorithm was incorporated into IFDES in such a way that no special formulation of the problem but the one described above is needed.

Another Hitting algorithm uses random search combined with linear search. The computer generates random numbers which, after normalization, are assigned to the initial values of variables X. Then corresponding values of C and D are calculated. This procedure is being repeated until a new current value of Dk becomes less than the initial one. In this case the linear algorithm begins to work trying to make steps in the direction that has brought the improvement. If it does not succeed in further improving the value of Dk, then the random generator is reactivated. The design process is being repeated until the solution is found, i.e. all Cj belong to Fj.

The Matrix Generator is now realized by means of the Lotus 1-2-3 package in which IFDES parameters Aij, A0 and others are calculated by the given parameters of the FMS model and are stored in the Lotus spreadsheet. "READ" and "WRITE" programs make it possible to exchange data between the Matrix Generator, the Data Bank and IFDES. All the above mentioned programs are linked together. The user operates IFDES with the help of the developed Menu and has a possibility to introduce new values of all characters at any time of IFDES work and to operate all the necessary programs forming IFDES.

9. PRODUCTIVITY INDICATORS AND VALUE FUNCTIONS

Relative Indicators

In the above example only absolute output figures have been used to compare different solutions and alternatives. However, sometimes the relative output figures are more suitable for a relative comparison of two solutions.

The following, commonly used relative indicators can be easily calculated from the basic model.

Availability for machine i can be calculated as follows:

$$av_j = \frac{Tmax - Td_i}{Tmax} \tag{28}$$

and for the system

$$AV = \frac{m\ Tmax - Td}{m\ Tmax} \tag{29}$$

The utilization rate for machine i obeys

$$u_i = \frac{\sum_i (Tij + tij)vibi}{Tmax} \tag{30}$$

and for the system

$$U = \frac{\sum_i \sum_j (Tij + tij)vibi}{m\ Tmax} \tag{31}$$

The average machining time per part (total active annual time/number of produced parts) is

$$T_M = \frac{\sum_i \sum_j (Tij + tij)vibi}{\sum_i vibi} \tag{32}$$

For the average throughput time (the average time to get one part produced) the following estimates can be used

$$T'_T = \frac{\sum_i \sum_j (Tij + tij)bi + \sum_i \sum_j Tb_{ij} + \frac{Td}{Tmax} \cdot \sum_i bi}{N} \tag{33}$$

and

$$T^{z}_{T} = \frac{\sum_{i}\sum_{j}(Tij + tij)vibi + \sum_{i}\sum_{j} Tb_{ij}\, vi + Td}{\sum_{i} vibi} \tag{34}$$

Two relative cost figures can be used to indicate production costs.

The <u>unit time cost</u> can be defined as the total discounted annual costs per total annual production time, or

$$k_{T} = \frac{(K + y\cdot labor)/y}{\sum_{ij}(Tij + tij)vibi} \quad , \tag{35}$$

where "labor" is direct labor costs and y is the planned life time of the system.

The <u>unit part cost</u> (the cost of a part i) is defined as calculated with the help of the share of the production time of part i from the total manufacturing time, or

$$k^{i}_{u} = k_{T} \cdot \frac{\sum_{j}(Tij + tij)vibi + \sum Tb_{ij}vi}{vibi} \tag{36}$$

$$= k_{T} \left[\sum_{j}(Tij + tij) + \sum_{j} \frac{Tb_{ij}}{bi} \right]$$

From the previous equations it can be easily seen that equation (35) can be written in the form of

$$k_{T} = \frac{(K + y\cdot labor)}{y\cdot m\ Tmax \cdot U} \quad ,$$

where U is the system utilization rate.

The equations also reveal the role of <u>time</u> in manufacturing costs. Because of the high fixed costs it is the time, which matters, not the variable costs. Also, due to the importance of time, it is easily recognized that, the higher utilization rate of the system, the lower are the relative costs. It can even be profitable to increase fixed costs (like improved training, more reliable software, better planning process), if the utilization rate is sufficiently improved to overcome the increased costs.

Utility and value functions

Depending on the goals of the system use and design, different value functions can be used to express the goal and compare different solutions.

The following list of value functions can be used to form multi-criteria value functions.

(max) $V_1 = \Sigma\ Pivi$ (priorities or values to different parts)

(max) $V_2 = P_U \sum_{ij} (Tij + tij)vibi$ (max. utilization rate)

(min) $V_3 = P_D Td$ (min. disturbance time or max. availability)

(min) $V_4 = P_T T_T$ (min. throughput time ≈ min. work in progress)

(max) $V_5 = P_G \sum_{i} P_{Gi}\ Gi\ bivi$ (max. flexibility or complexity potential)

(max) $V_6 = P_L \sum_{i} \sum_{j} L_{ij}\ bivi$ (max. flexibility or complexity potential)

(min) $V_7 = K$ (min. fixed costs)

Of course, functions V_5 and V_6 are special cases of function V_1, but can be used to better emphasize the future potential.

10. DISCUSSION

Although the above FMS model has been simplified, it shows as such many useful properties. For instance, it helps the designer to make a tradeoff between capacity, part family, batch sizes, throughput time and expected costs. It also explains the tradeoff between conventional systems and FMS-type production. It forms the necessary first step to understand investment decision-making and selection between different manufacturing systems. Thus the model can explain different techno-economic factors behind the planned benefits as well as the diffusion factor on the company level.

Thus it is the first step towards an investment decision-making aid and it can also contribute to problems which are of great importance, but were not tackled in this paper. These are problems of scenario preparation for the FMS analysis, consideration of nonlinear relationships between FMS parameters, economic risk factors and life-cycle cost concepts. To take into account these factors it is planned further on to develop some new features of the model that are supposed to be more complicated. Some discussions of the above problems will follow. It should be pointed out that the general methodology and the Feasible Domains approach developed for the analysis of the FMS productivity and flexibility remains the same but the concrete algorithms could be different (nonlinear, stochastic, etc.), depending on the type of the FMS model.

Moreover, to fully understand and model the benefits of FMS, we need more proper measures on complexity and flexibility, which take into account different shapes and surfaces of parts, tooling, functions, accuracy, limits of dimensions, etc.

Scenario preparation

This problem is related to the first high level of the process of FMS analysis and planning. Its solution demands detailed expert analysis of the FMS and production situation. Now there are some good sophisticated methods for decision making for discrete systems. Practically useful approaches that can be applied here are described, for example, in Lewandowski et al. (1986) and Larichev (1979).

Nonlinear cost model

In this paper a simple cost relationship, based on the empirical findings from practical systems (Sheinin and Tchijov, 1988; Ranta, 1988) was used as a first order approximation of the relationship between costs and systems properties. In practice the relationships are nonlinear, eg. there are many saturation effects. In order to have a nonlinear cost model the solution algorithm has to be changed -- a method capable of solving nonlinear optimization problems has to be chosen to develop different solution scenarios. One candidate for this purpose is, e.g., DIDAS (Dynamic Interactive Decision Analysis and Support), developed at IIASA (Kaden et al., 1984).

Economic risks

As was mentioned above there are problems related to the changing environment and technological properties of the system. The first feature can be called static risk and is related to fitting the system properties (part family, complexity, etc.) to the respective needs. This feature can be taken into account through different value functions presented in the previous chapter.

The dynamic economic risk is partly related to continuously changing markets and is therefore dependent on the time period under consideration and on the whole life cycle of the system. The second feature is related to life cycle costs, taking into account the balance between planning and training against long-term availability of the system.

The first characteristic is related to the changing product properties, which means that there is a changing demand for part family and complexity to be produced. If the production systems is not able to adapt to the changing requirements, it can be the major source of the economic risk of investment. By nature, this is a dynamic and stochastic problem and there is a request for stochastic models analyzing different alternatives during the design.

IIASA has its own results in solving stochastic programming problems. Good candidates for the purpose of risk analysis in this context are the algorithms described in Gaivoronski (1988).

The second characteristic requires a study of the complex relationships of the different phases of the systems life cycle. The key property is the availability of the system. But the question also refers to which factors influence the availability (and non-availability), how can these factors be controlled during the systems design, and which are costs of availability. The second key property is a rapid startup of the systems. This can also be influenced by the system design. By nature, the life cycle cost model should be a statistical model.

APPENDIX A: NUMERICAL EXAMPLE OF THE FMS MODEL

To show the application of the suggested approach, consider a basic example of an FMS consisting of one Turning machine, two Machining centers, one grinding machine and automatic transportation and warehouses for systems integration. This FMS is to produce 13 parts annually. We consider that the batch size is equal for all 13 parts and can take different values (say: 5, 10, 20, 40). The lay-out of the system and the time estimates are drawn from a real case.

Other parameters of the FMS are shown in Tables 2-5.

Note: in this example we consider that efficiency Ej in (10) is simply estimated by average tooling speed; transportation costs were not considered.

We set the lower values for Time and Cost to be 0 in order to achieve as low values for these factors as possible. The parameters of inequality (15) for this example can be expressed in the following form (see the description of the model above):

$$\left.\begin{array}{l} Ais = bi \times (Tij + tij),\ Cs0 = 0, \\ Csmin = Tjmin,\ Csmax = Tjmax. \end{array}\right\} \text{ for } s = 1..j..m.$$

$$\left.\begin{array}{l} Ais = \sum_{j}(bi \times (Tij + tij)) + \sum_{j}(Tbij) + Tdi \times m \\ As0 = \sum_{i}(Tdi \times Gi) + Td^{s} \times SS - Td^{pl} \times PL, \\ Csmin = m \times Tmin,\ Csmax = m \times Tmax. \end{array}\right\} \text{ for } s = m+1$$

$$\left.\begin{array}{l} Ais = Pvi + Svi + S^{*} + Tvi + T^{*}, \\ As0 = \sum_{i}(S_{Gi} \times Gi) + \sum_{i}(S_{Li} \times Li) + \sum_{j}(S_{Ej} \times Ej) + \\ + \sum_{i}(P_{Gi} \times Gi) + \sum_{i}(Pbi \times bi) + \sum_{j}(M_{Ej} \times Ej) + \\ + \sum_{i}(R_{Li} \times Li) + \sum_{i}(R_{Gi} \times Gi) + O^{*} \times PL + \sum_{i} TiGi, \\ Csmin = Kmin,\ Csmax = Kmax. \end{array}\right\} \text{for } s = m+2$$

Table 2. Part family of the numerical example, complexities and tooling times of different parts

i	Vmin	Vmax	G	Ti1 min	ti1 min	Ti2 min	ti2 min	Ti3 min	ti3 min	Ti4 min	ti4 min	Tbi min	L
1	500	700	4	20	2.0	20	2.0	20	2.0	8	4.0	4.0	50
2	2000	2500	2	12	1.6	6	1.2	6	1.2	4	2.0	2.0	50
3	1500	2000	3	20	2.0	14	2.0	14	2.0	8	4.0	4.0	50
4	1500	2000	4	20	2.0	20	2.0	20	2.0	8	4.0	4.0	50
5	1000	1200	4	40	1.2	10	1.2	10	1.2	8	4.0	4.0	50
6	100	300	6	20	1.6	20	2.0	40	2.0	20	4.8	4.8	50
7	200	300	8	40	2.0	40	2.4	60	2.4	40	6.0	6.0	50
8	3000	3500	2	12	1.6	6	1.2	6	1.2	4	2.0	2.0	50
9	3000	3500	2	12	1.6	6	1.2	6	1.2	4	2.0	2.0	50
10	1500	2000	3	12	0.8	8	0.8	8	0.8	8	2.0	2.0	50
11	200	300	9	48	4.0	60	4.0	60	4.0	80	6.0	6.0	100
12	150	250	10	60	5.0	45	5.0	45	5.0	80	6.0	6.0	100
13	100	200	10	0	0.0	40	5.0	60	5.5	50	8.0	8.0	100

Table 3. Disturbance coefficients and time constraints

b Td min	G Td min	s Td min	pl Td min	SS mln line	PL h/per	Tmax thous min	Tmin thous min
3	40	0.05	3	1	100	316.8	158.4

Table 4. Cost coefficients

S_G 10^4	Sv	Sl 10^2	S*	P_G 10^3	Pb 10^3	Pv	M_E	R_L 10^2	R_G 10^3	O*
0.5	20	3	10	10	3	200	100	5	10	100

Table 5. Cost constraints and efficiency coefficients

S_E	Kmin mln $	Kmax mln $	E1 th.	E2 mm/min th.	E3 th.	E4 th.
2	3	7	3	3	3	6

All parameters of (15) were calculated by the above expressions and their numerical values were introduced into IFDES. (A separate program was worked out to calculate parameters for (15) by given values of real FMS parameters: see Tables 2-5).

The aims of the study were:

- to analyze the load of machines and balance it if necessary,
- to analyze Cost and Time factors of production for different lower and upper values of product volumes vi, batches bi, and different sets of parts.

For all these investigations the LP algorithm was activated to find the values of the output parameters (criteria): Tj - production time for each machine, TΣ - sum production time, and K - cost of production of the given set of parts. On the basis of the results of the calculations the user could vary batch sizes, volumes of parts, machining times for machines and some other parameters trying to reach the given aims.

To demonstrate the capabilities of the above approach the influence of batch size on the Time and Cost parameters of the described FMS model was analyzed. Figure 5 shows the results of calculations for the unbalanced case (machines 1 and 4 have different load: machine 1 is overloaded, while machine 4 has reserves). Figure 6 shows the results for the case in which their load is balanced. Figure 7 contains the graph showing the influence of the batch-size on the Time and Cost factors of FMS production. For this case batch sizes for all the considered 13 parts were equal and were changed simultaneously. One can see that value 10 is critical for these factors and holds their minimum values.

Another example shows the results of the analysis of the influence of the lower values for production volumes of the given parts on the output factors: production times Tj, TΣ - sum of production time, and K - cost of production. Two cases were taken into consideration.

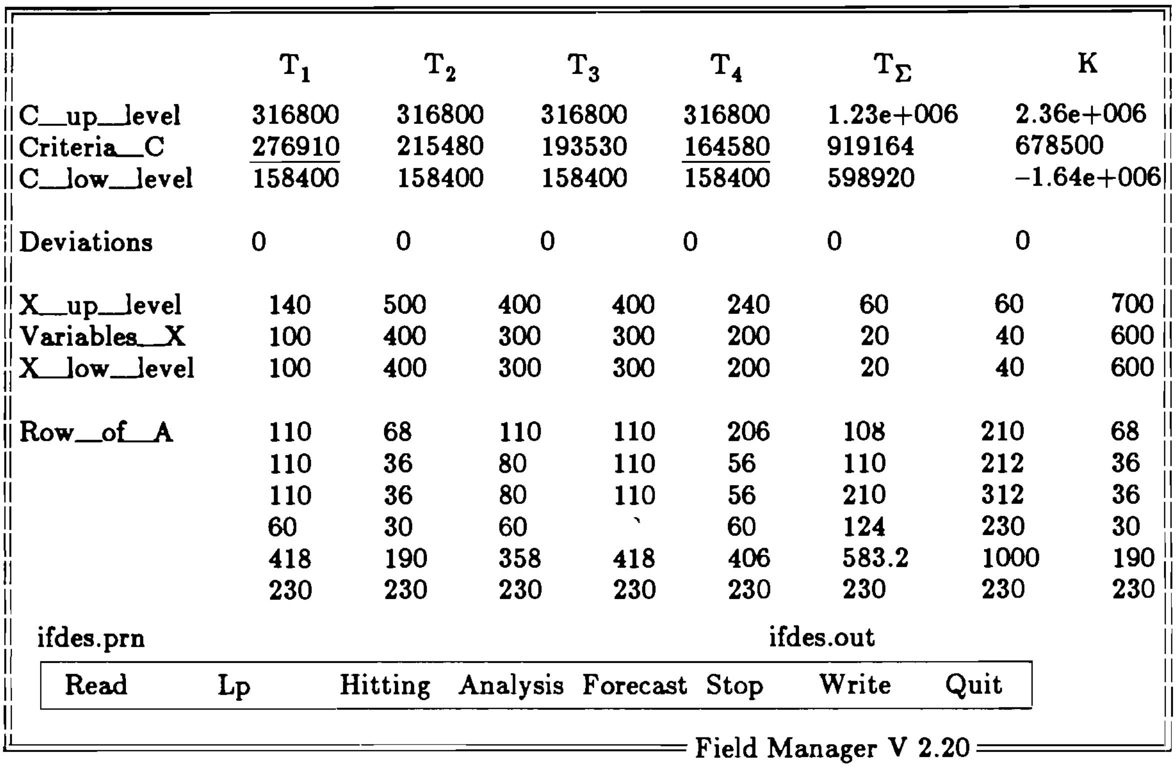
Case a) - for 13 parts with batch sizes given in Table 6.

Case b) - with additional 3 complex parts (see Table 7).

In both cases the lower levels of the production volumes for all considered parts were decreased by 10%, 20%,... Values for Tj, TΣ, K were calculated by IFDES using the LP algorithm. The results are shown in Figures 8 - 13. It could be seen that the 30% decrease of Vimin holds the inflection point after which the output parameters are stabilized. Thus it is possible to choose the planned volumes of different parts with good estimations for Time and Cost factors of production and to repeat the same study for different combinations of machines.

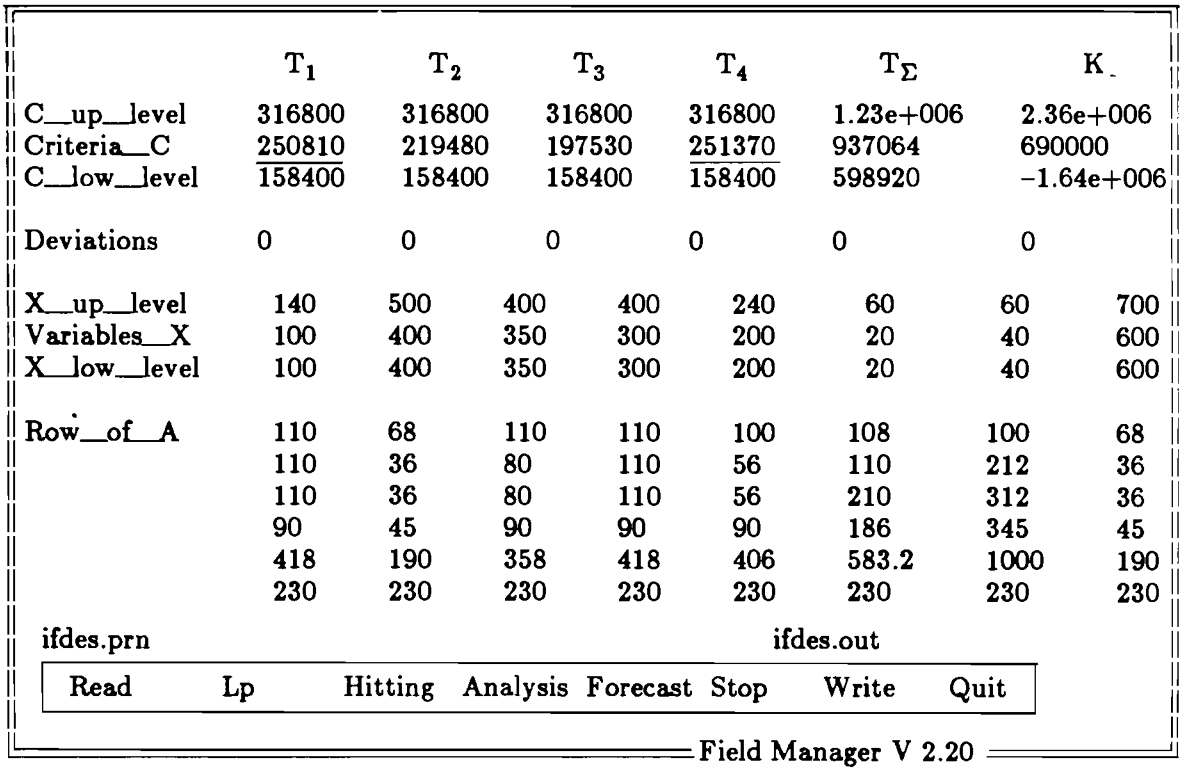
Moreover, it is possible to compare relative benefits of different layouts (even conventional, functional layout compared to cell layout) or select a part family for fixed layout and then also understand the relative benefits of FMS-systems. From the result it is also apparent that the proper part family and the optimal mixture of part volumes are depending on the capacity in use (-10% maximum or -20% maximum). The result as such sounds reasonable.

As a conclusion it can be pointed out that the approach and the interactive system IFDES allow to analyze the main characteristics of FMS



```
                T1       T2       T3       T4       TΣ          K
C_up_level      316800   316800   316800   316800   1.23e+006   2.36e+006
Criteria_C      276910   215480   193530   164580   919164      678500
C_low_level     158400   158400   158400   158400   598920      -1.64e+006

Deviations      0        0        0        0        0           0

X_up_level      140      500      400      400      240      60      60      700
Variables_X     100      400      300      300      200      20      40      600
X_low_level     100      400      300      300      200      20      40      600

Row_of_A        110      68       110      110      206      108     210     68
                110      36       80       110      56       110     212     36
                110      36       80       110      56       210     312     36
                60       30       60                60       124     230     30
                418      190      358      418      406      583.2   1000    190
                230      230      230      230      230      230     230     230

  ifdes.prn                                     ifdes.out
```

Figure 5. Poorly balanced machines 1 and 4.



```
                T1       T2       T3       T4       TΣ          K
C_up_level      316800   316800   316800   316800   1.23e+006   2.36e+006
Criteria_C      250810   219480   197530   251370   937064      690000
C_low_level     158400   158400   158400   158400   598920      -1.64e+006

Deviations      0        0        0        0        0           0

X_up_level      140      500      400      400      240      60      60      700
Variables_X     100      400      350      300      200      20      40      600
X_low_level     100      400      350      300      200      20      40      600

Row_of_A        110      68       110      110      100      108     100     68
                110      36       80       110      56       110     212     36
                110      36       80       110      56       210     312     36
                90       45       90       90       90       186     345     45
                418      190      358      418      406      583.2   1000    190
                230      230      230      230      230      230     230     230

  ifdes.prn                                     ifdes.out
```

Figure 6. Fairly balanced machines 1 and 4.

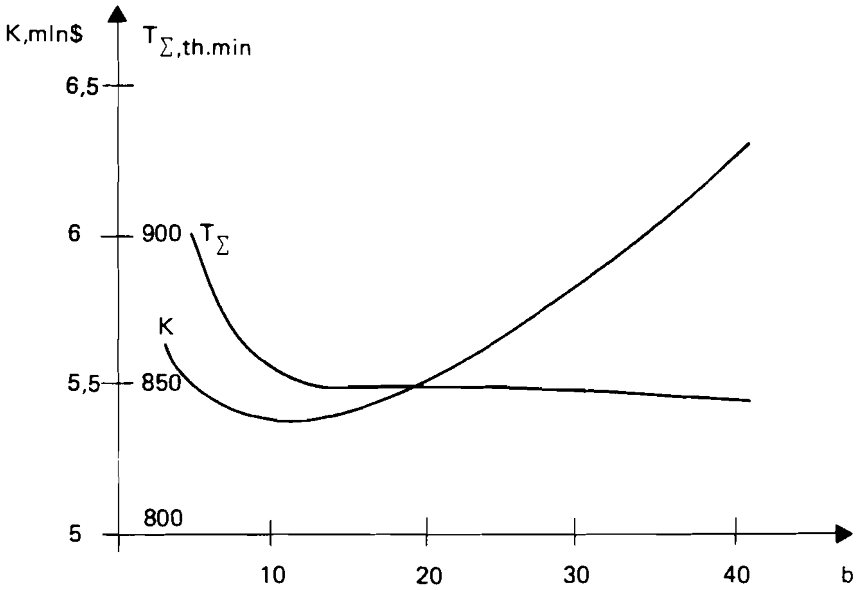


Figure 7. Batch sizes and costs and production times.

Table 6. The mixed batch sizes of the example

i	i	2	3	4	5	6	7	8	9	10	11	12	13
b	10	50	50	50	10	5	5	50	50	50	5	5	5

Table 7. Parameters of the extended FMS model

i	E	b	Vmax	Vmin	Ti1	ti1	Ti2	ti2	Ti3	ti3	Ti4	ti4	Tbi	L
14	10	5	150	50	60	5	45	5	45	5	20	2	15	100
15	12	5	150	59	90	10	60	5	60	60	30	2	20	100
16	8	5	150	50	60	5	60	5	60	60	20	2	15	100

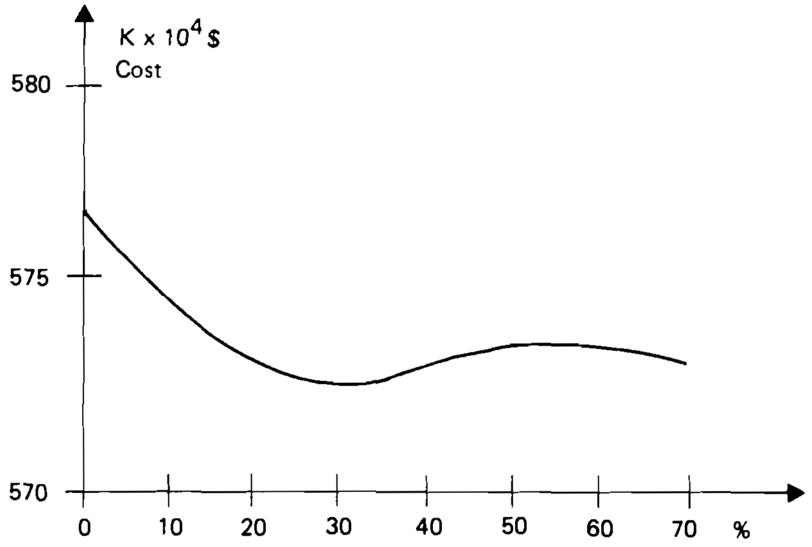


Figure 8. Decrease of Vimin, production volume (Case A) and costs.

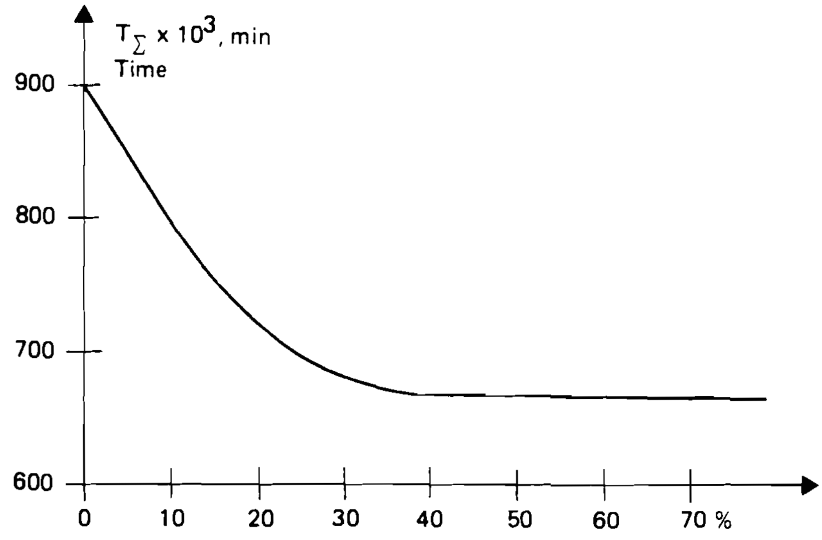


Figure 9. Decrease of Vimin, production volume (Case A) and production time.

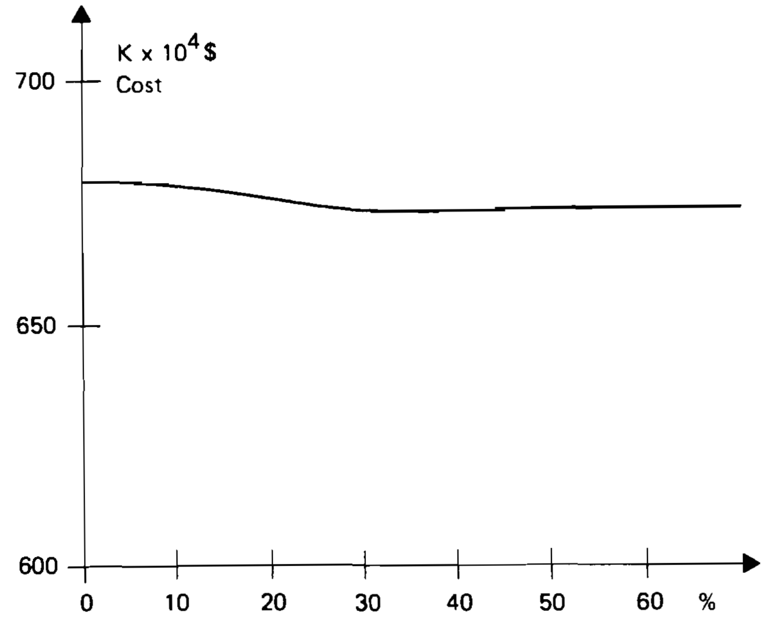


Figure 10. Decrease of Vimin, production volume (Case B) and production costs.

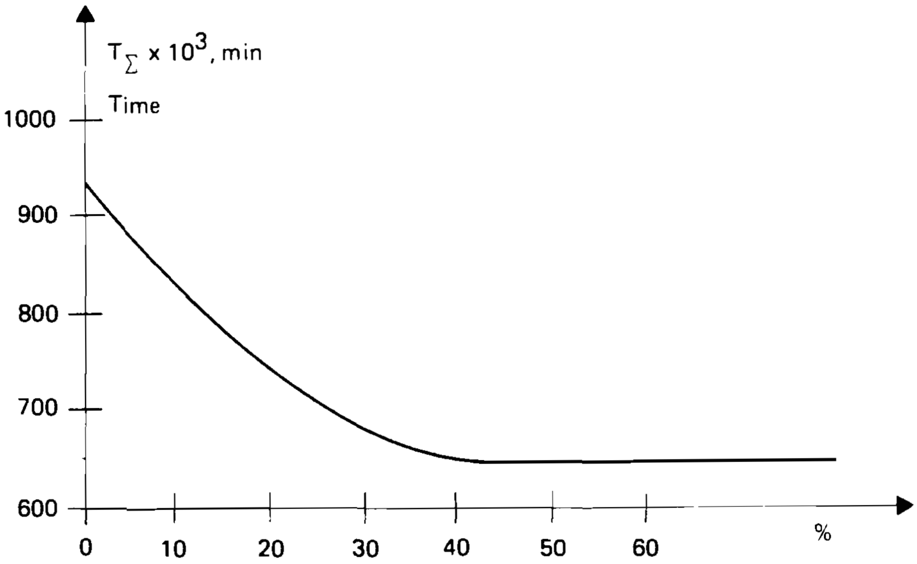


Figure 11. Decrease of Vimin, and production time (Case B).

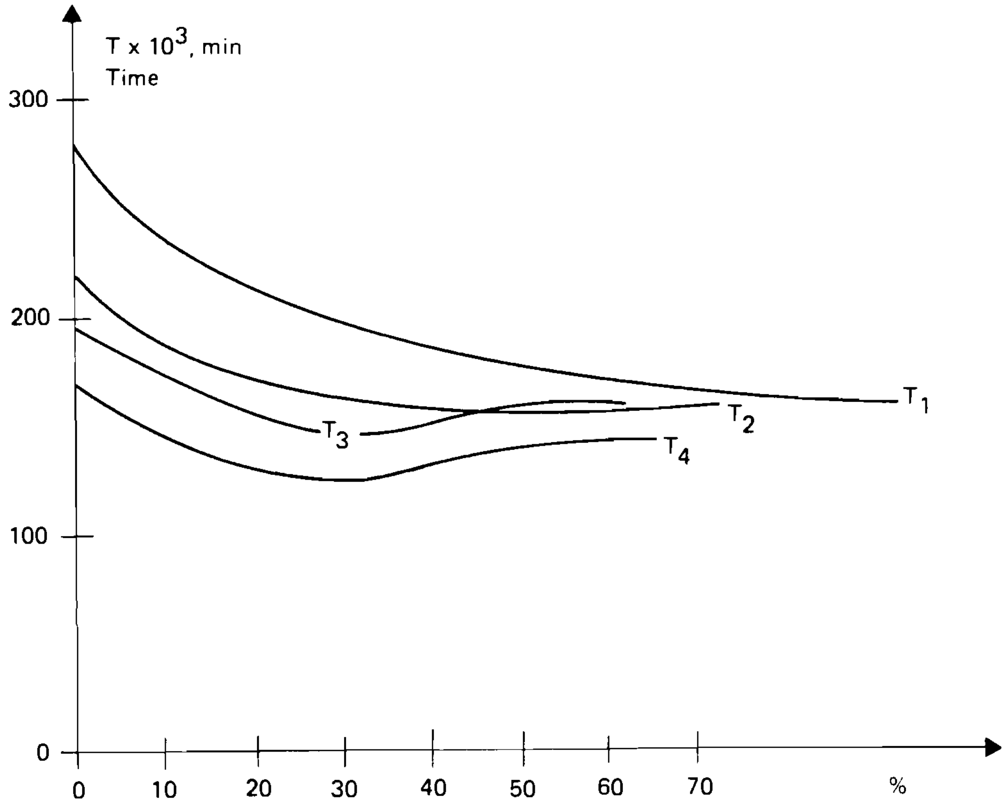


Figure 12. Decrease of Vimin (Case A) and production times.

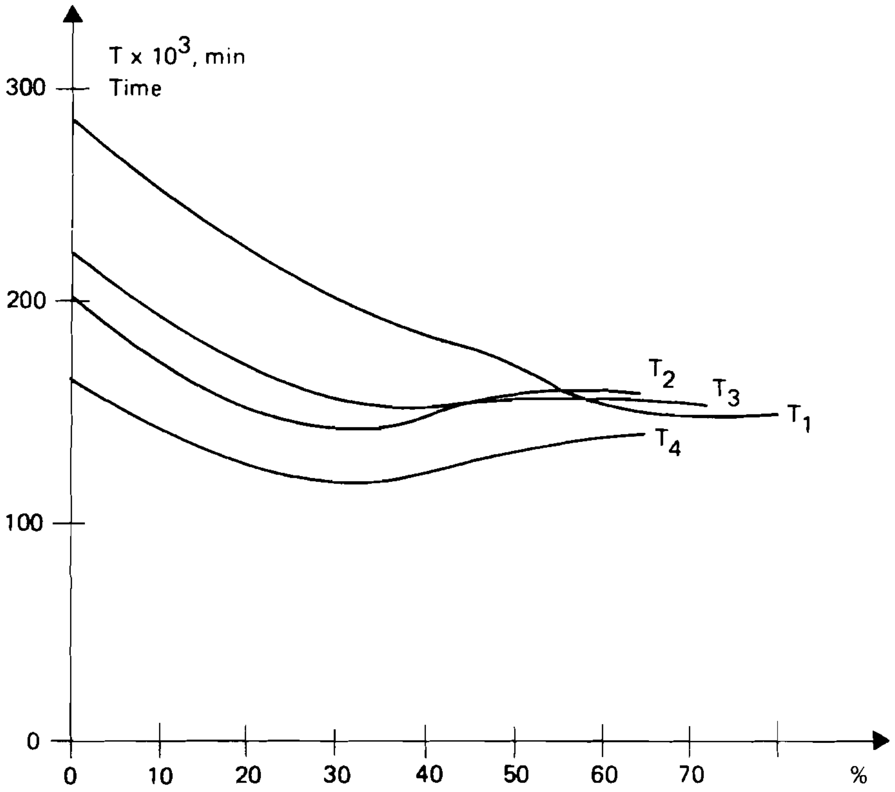


Figure 13. Decrease of Vimin (Case B) and production times.

and to play different scenarios of FMS realization. By changing FMS parameters it is possible to obtain satisfactory flexibility and productivity of FMS for the given parts and their production volumes. It is also possible to analyze and to provide recommendations for the usage of different machines in FMS and to balance their load in the most proper way.

APPENDIX B. DEFINITIONS

I. IFDES

Cj - criteria functions,

j - criteria number j = 1 ... m,

Xi - variables,

i - variable number, i = 1 ... n.

II. FMS Model

<u>Time terms</u>

V - sum of annual production volume for the given FMS,

Vi - annual production volume for the i-th part,

bi - batch size of the i-th part,

Tij - time needed for the machining of part i at machine j,

Tij - actual tooling time,

tij - overhead time,

Tbij - batch change time,

Td - technical non-availability time,

Gi - complexity of the i-th part,

SS - software size factor,

PL - personnel training factor.

<u>Cost terms</u>

K - cost of production,

Mc - machine costs,

Lc - tool costs,

Pc - pallet costs,

Sc - software costs,

Tc - costs of FMS transportation devices,

Oc - other costs.

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