WORKING PAPER

SELECTING A FLEXIBLE MANUFACTURING SYSTEM USING MULTIPLE CRITERIA ANALYSIS

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FOREWORD

In recent years, many manufacturing companies have adopted a flexible manufacturing strategy, seeking to improve the efficiency of their production process in order to gain an edge in the increasingly competitive market place. The decision of which specific flexible manufacturing system (FMS) to invest in is a complex strategic question, and calls for evaluating tradeoffs between multiple conflicting criteria, for instance involving the production capacity, machine investment and production costs and flexibility of the system.

This working paper introduces a user-oriented interactive decision support framework which can be used by management to solve this selection problem, first by pre-screening the typically relatively large set of available candidate configurations, and next by exploring tradeoffs within a specific FMS configuration, using a visual interactive multicriteria mathematical programming procedure.

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ABSTRACT

This paper describes a visually interactive decision support framework designed to aid the decision maker, typically top management, in selecting the most appropriate technology and design, when planning a flexible manufacturing system (FMS). The framework can be used in the pre-investment stage of the planning process, after the decision in principle has been made to build an FMS. First, both qualitative and quantitative criteria are used to narrow the set of alternative system configurations under consideration down to a small number of most attractive candidates. After this pre-screening phase, a multiobjective programming model is formulated for each remaining configuration, allowing the manager to explore and evaluate the costs and benefits of various different scenarios for each configuration separately by experimenting with different levels of batch sizes and production volumes. The system uses visual interaction with the decision maker, graphically displaying the relevant tradeoffs between such relevant performance criteria as investment and production costs, manufacturing flexibility, production volume and investment risk, for each scenario. Additional criteria, when relevant, can be included as well.

The ease of use and interpretation and the flexibility make the proposed system a powerful analytical tool in the initial FMS design process. The insights gained from experimenting with the different scenarios form the basis of understanding the anticipated impact of techno-economic factors on the performance of the FMS configuration, and provide valuable information for the implementation stage of building the FMS. An example using real data from a case study in the Finnish metal product industry is provided to illustrate the methodology.

INTRODUCTION

Many companies seek to maintain or gain a competitive edge in the market place by exploiting the advantages of modern manufacturing technologies. One such technology which has become increasingly popular over the past decade is that of flexible manufacturing systems (FMS) (Buzacott and Yao 1986, Jaikumar 1986, Ranta et al. 1988). The primary goal of implementing an FMS is to make the production process as versatile or flexible as possible, in terms of among others an ability to produce a variety of products of different degrees of complexity, short delivery times, easily changed production volumes and batch sizes, and flexible production scheduling (Ranta 1989, Whitney 1985). A higher flexibility in general will enable the company to more easily adjust to changes in the market place and customer needs, while maintaining high quality standards for the products. Prior to implementing an FMS, however, a careful feasibility and performance analysis is needed in which the impacts of various technological, economic, design, managerial and social factors associated with the FMS are considered. Recent studies have shown that the most important of these factors are related to the design, implementation, social and managerial aspects of the FMS, rather than the technology itself (Ranta 1989, p.2). Thus, the FMS selection problem is a strategic question which typically has to be decided by top level management (Choobineh 1986, Ranta 1989, Wabalickis 1988).

In most situations, a number of alternative FMS configurations are available. Given the strategic nature of the FMS investment, the question is how to effectively analyze which of the feasible configurations is the most appropriate. Two widely used approaches to analyze the performance of FMS configurations are simulation studies and studies using analytical models. Buzacott and Yao in their review article of FMS note that "while simulation models are of great value for evaluating specific systems designs, analytical models are superior in terms of the amount of insight which they give." (1986, p.902) Moreover, they conclude their paper by stating that "...due to their complexity, the new manufacturing systems now being developed are only partly understood from a system perspective (Gershwin et al. 1984)..." so that "...analytical models can provide the necessary insights."

This paper belongs to the category of analytical models, and presents a decision support framework which can aid the decision maker (top level management) in the pre-investment stage of designing the most suitable FMS. The main contribution of this paper is to provide a structured framework to support management's general understanding of the dynamics of the decision problem at hand, and specifically to assist management in selecting the "most appropriate" FMS design from a set of available candidate configurations, through extensive scenario analysis and evaluation of the tradeoffs between the various decision criteria. Of course our framework does not comprehensively cover the scope of the complex overall decision of acquiring an FMS. Therefore the decision maker should use our decision support system in conjunction with other complementary types of analysis, such as a financial feasibility study and a study of the organizational impacts (retraining workers, new structures etc.) of the FMS conversion.

Our decision support framework consists of two phases. In the initial pre-screening phase, the executive support system Expert Choice (Forman 1987) is used to narrow the usually relatively large group of candidate configurations down to the three or four "most attractive" configurations. A nice feature of this software package is that it allows for both qualitative and quantitative factors and criteria to be considered. The remaining three or four candidate configurations are then further analyzed in more detail in the second phase. This analysis in phase two is quantitative, and involves solving a multiobjective mathematical programming formulation of the problem in which for each configuration various scenarios are explored interactively. The decision maker evaluates the tradeoffs between relevant decision criteria such as production volume, investment costs and flexibility, by varying the batch size and production volume of each part and controlling the utilization of the machines. The VIG package (Korhonen 1987) was selected for this analysis because its graphical displays and user-friendly interaction between decision maker and model make it well-suited for analyzing this type of problem under consideration.

The remainder of the paper is organized as follows. First, the general decision support system methodology and the multiobjective programming formulation are introduced, with a detailed discussion of the different components related to costs and flexibility. Next, a specific application of the decision support system to a Finnish metal product firm is introduced, followed by an exposition of how the decision support system can be used in practice. The paper concludes with final remarks.

DSS FRAMEWORK

As previously mentioned, the proposed methodology consists of two phases. In each phase, specialized analytical tools with a high power user interface are used to analyze the pertinent questions. It is assumed that prior to using the decision support system, initial data have been collected and a preliminary study has been performed to identify and globally characterize the set of all candidate design configurations for the FMS. A general description of the two phases follows.

Phase One

The initial number of available alternatives may be relatively large and therefore difficult to manage in terms of evaluating the tradeoffs. Research has found that the human mind can effectively evaluate tradeoffs between at most five to seven alternatives simultaneously

(Steuer 1986). The personal experience of one of the authors with decision makers in previous interactive computer applications involving multiple criteria confirms this finding (Stam et al. 1987). For this reason, a pre-screening procedure is applied in phase one to narrow the list of candidate FMS configurations to a more managable number. Depending on the specific application, a reasonable number appears three or four alternatives, but in some situations many attractive alternatives may exist, whereas in other cases only a few viable configurations are available. The commercially available package Expert Choice (Forman 1987) allows for the analysis of tradeoffs related to quantitative criteria such as costs, as well as qualitative criteria such as organizational and social impacts of the FMS design. Thus, a useful aspect of the pre-screening analysis is that all FMS design configurations can simultaneously be evaluated both on "hard" criteria which can be expressed numerically and on "soft" criteria which cannot meaningfully be expressed in terms of numbers. A second package which can be used to analyze discrete alternative multicriteria problems with quantitative as well as qualitative criteria is DISCRET (Majchrazak 1988), developed in Poland in conjunction with the International Institute for Applied Systems Analysis (IIASA) in Austria. DISCRET is based on the reference point method developed by Wierzbicki and Lewandowski (Lewandowski and Wierzbicki 1988; Wierzbicki 1979, 1982).

Expert Choice is quite powerful and has been used in numerous real applications (Saaty 1987, Forman 1987, Dyer et al. 1988) and executive decision situations. The theoretical foundation of Expert Choice is based on the Analytic Hierarchy Process developed by Saaty (1980, 1987). This approach has recently been recommended by Wabalickis (1988) as a useful methodology to justify an FMS. However, Wabalickis did not use the Expert Choice software, but his own calculations and computer programs to calculate the results, and his approach was quite limited and not interactive, in contrast to our approach (using Expert Choice) which is both interactive and on-line, and flexible in the way in which the decision maker prefers to provide the necessary information.

The main idea behind the modeling philosophy of Expert Choice is to chunk the decision problem into smaller subproblems, making it easier for the decision maker to evaluate tradeoffs. For instance, a global criterion such as FMS investment and production costs can be subdivided into several subcriteria such as software costs, tool costs and training costs. These subcriteria can in turn further be refined, creating a hierarchical tree structure of the decision problem. The lowest level of this tree contains the alternatives, in our application the different possible FMS configurations.

The manager can evaluate these alternatives in two different ways. One is to make pairwise comparisons, first between each of the global criteria at the highest level of the hierarchy, making judgments on their relative importance, followed by comparisons of the lower level criteria. Finally the alternatives are compared pairwise according to their importance with respect to each criterion. The pairwise comparisons are used to calculate a composite importance weight for each of the alternatives, resulting in a final ranking of the alternatives. The alternative with the highest ranking is the "most preferred" one, given the preference information provided by the decision maker through the pairwise comparisons. This approach, however, requires a multitude of pairwise comparisons, and is not feasible if the number of alternatives or criteria is considerable. The other way to evaluate the alternatives is the ratings approach, where the alternatives are directly rated with respect to each of the criteria, after which again the composite ranking score is calculated. This option is particularly useful if the number of alternatives is too large to make all pairwise comparisons. After the ranking process of alternatives has been completed, Expert Choice facilitates extensive graphical and numerical sensitivity analyses where the sensitivity of the ranking to changes in the manager's importance judgments can be tested.

Our use of the final rankings provided by Expert Choice differs slightly from the way in which these are typically used. In most cases, the alternative with the single highest ranking is selected as the "most preferred" and implemented. In our approach, however, the Expert Choice analysis is only a pre-screening phase where undesirable and less attractive alternatives are eliminated from further consideration. Therefore rather than one alternative, a small group of alternative candidate configurations is selected for the analysis in the second phase.

Phase Two

Phase two differs from phase one in several ways. First, in the pre-screening phase only general judgments about the level of each criterion are required, while in the second phase detailed quantitative information is needed. For intance, in the pre-screening process investment costs can be described in terms of categories such as "very high," "high," "average" and "low," while in phase two numerical (ratio scale) values are used and the tradeoffs between the criteria are of a quantitative nature. Second, only a small number of alternatives remain and are analyzed in more detail using quantitative techniques. Third, in the second phase the methodology seeks to explore the performance tradeoffs between the relevant criteria of each remaining FMS configuration, subject to the physical limitations and performance characteristics of the design. This analysis requires formulating the relevant aspects of each FMS configuration in terms of a multiobjective mathematical programming problem. A separate model should be formulated for each configuration, because each has its own unique specifications. It should be noted that Expert Choice does not have the ability to deal with this type of multiobjective decision model.

In the formulation, the operational decision variables include the quantity of each part to be produced and the batch size of each part. The constraints include physical limits to the amount of time available on each machine. As alluded to above, the criteria include the costs associated with acquiring the FMS configuration, the total production volume of each member of the part family, and the degree of flexibility of the configuration. The previously determined configuration-specific parameter coefficients are used as input for the formulation. It is very important that the input parameters are reasonably accurate, because the results of the multiobjective analysis can be sensitive to the values of these coefficients.

After considering a number of different multicriteria software packages, the Visual Interactive Goal Programming package (VIG) (Korhonen 1987) was selected for the analysis in phase two, mainly because of its attractive graphical user interface. The method allows the decision maker to move freely on the Pareto optimal surface. He can search the set of efficient solutions by controlling the speed and the direction of the motion (Korhonen and Soismaa (1988)). A solution is said to be Pareto optimal or efficient if none of the criteria can be improved without sacrificing at least one of the other criteria. Thus, the decision maker can be confident that inferior solutions are automatically eliminated, and only relevant solutions will be considered throughout the interactive decision process. Thus, at any time during the interactive process, the decision maker has on-line control over the decision parameters (batch size and production volume of each member of the part family), controls the target utilization rates of the machines, and can directly observe the changes in the criterion values and the associated tradeoffs between criteria on the screen in the form of easily interpreted bar graphs. The mathematical details of VIG can be found in Korhonen and Laakso (1986). Korhonen and Wallenius (1986) describe an implementation of the method.

MULTIOBJECTIVE FORMULATION

The two major critical resources in modeling the FMS decision are on the one hand the capital needed for the FMS investment, which largely depends on the costs of the FMS configuration, and on the other hand time, as each machine can operate only for a limited number of hours annually. The cost and time resources are interrelated and often conflicting parameters. Fore instance, more time efficient machines are obviously more expensive, but can provide a more efficient tooling times. The nature of these two scarce resources is described next. The model formulation closely follows Ranta and Alabian (1988) and Ranta (1989). A concise list of all equations, criteria, decision variables, model parameters and coefficients is given in Appendices 1-3.

Suppose a particular FMS configuration consists of m machines which are to produce n different parts. Define the actual tooling time of part i on machine j by T_{ij}, and the unit overhead time including changing, waiting, checking and repairing by t_{ij}. Furthermore, let the batch size and the number of batches produced per period (e.q. annualy) of part i be given by b_i and v_i, respectively, so that the total production volume per period of part i is represented by $V_i = b_i*v_i$, and the total production volume of all parts combined by $V = \sum_{i=1}^{n} V_i$.

Costs

All cost figures are expressed in U.S. dollars. The total costs of the FMS per period may be divided into machine costs (C_M), tool costs (C_L), parts pallet costs (C_P), software costs (C_S), transportation costs (C_T) and other costs (C_O). Thus, total costs C can be represented as (1):

$$C = C_M + C_L + C_P + C_S + C_T + C_O \tag{1}$$

Each of these cost components is explained next. Assuming only the direct investment costs are included in the machine costs, C_M can be written as (2),

$$C_M = \sum_{j=1}^{m} e_j*M_j, \tag{2}$$

where M_j is the direct investment cost of machine j per unit produced, discounted and prorated over the planned lifetime of the machine, and e_j is the relative efficiency of machine j, which can be expressed in terms of the time needed for the machining of one unit of part i on machine j ($T_{ij}+t_{ij}$) and the total production volume of the parts per period, b_i*v_i, weighed by the coefficient e_{ij} which represents the relative efficiency of machine j on part i. Thus, e_j is given by (3),

$$e_j = \sum_{i=1}^{n} e_{ij}*b_i*v_i*(T_{ij} + t_{ij}) \qquad (j = 1,...,m) \tag{3}$$

The tool costs C_L depend on the complexity of the parts and the number of tools needed, and follows in (4),

$$C_L = \sum_{i=1}^{n} q_{gi}*g_i + \sum_{i=1}^{n} \sum_{j=1}^{m} q_{ij}*l_{ij}, \tag{4}$$

where g_i is the complexity of part i as measured by the form of the part, precision and other factors, and l_{ij} is the number of tools needed to produce part i on machine j, while f_i and f_{ij} are appropriate scaling coefficients.

The parts pallet costs depend on part complexity, batch size and the number of batches produced per period of each part:

$$C_P = \sum_{i=1}^{n} p_{gi}*g_i + \sum_{i=1}^{n} p_{bi}*b_i + \sum_{i=1}^{n} p_{vi}*v_i, \tag{5}$$

where p_{gi}, p_{bi} and p_{vi} are part-dependent scalar values.

Empirical studies have shown that software costs are related to numerical control (NC)-programs, scheduling and communication algorithms, and to the amount of interfaces needed (Ranta 1989). Thus it is reasonable to write the software costs C_S as follows:

$$C_S = \sum_{i=1}^{n} s_{gi}*g_i + \sum_{i=1}^{n} (s+s_{vi})*v_i + \sum_{i=1}^{n} \sum_{j=1}^{m} h_{ij}*l_{ij} + \sum_{j=1}^{m} s_{ej}*e_j, \tag{6}$$

where the first term is related to software complexity, the second to the number of batches produced per period, the third to tool management, and the fourth to machine efficiency. The terms s, s_{gi}, s_{vi}, h_{ij} and s_{ej} are constant coefficients.

The internal transportation costs C_T include costs associated with transportation devices and storage, and is given by (7),

$$C_T = u*V + \sum_{i=1}^{n} u_i*g_i + \sum_{i=1}^{n} u_{vi}*v_i, \tag{7}$$

which depends on the capacity of the system V, the complexity of the parts g_i and the number of batches v_i. The coefficients u, u_i and u_{vi} are scalars.

Finally, the remaining costs are represented by the category of other costs (C_O):

$$C_O = C_{TR} + C_{RES} \tag{8}$$

C_O includes personnel training costs C_{TR}, ($C_{TR} = c_{PL}*PL$, where PL is the number of employees to be trained), and residual costs C_{RES}. These costs do not depend on the decision variables (batch size and production volume of the parts).

Time

The second scarce resource is machine time. The unit of all time figures is in minutes. The total time machine j is used during the period is given by T_j in (9),

$$T_j = \sum_{i=1}^{n} (T_{ij} + t_{ij})*b_i*v_i, \qquad (j = 1,...,m) \tag{9}$$

where the parameters are as defined above. The technical nonavailability time or machine disturbance time of machine j (T_{dj}) depends on part complexity and the number of batches of each part type, on the size and complexity of the software needed (S_j) and a personnel training factor. Thus, T_{dj} can be expressed as in (10):

$$T_{dj} = \sum_{i=1}^{n} d^{g}_{ij} * g_i + \sum_{i=1}^{n} d^{b}_{ij} * v_i + d^{s}_{j} * S_j - d_j^{PL} * PL \qquad (j = 1,...,m) \qquad (10)$$

The coefficients d^{g}_{ij}, d^{b}_{ij}, d^{s}_{j} and d^{PL}_{j} are positive scaling constants. The disturbance formula described in (10) has an empirical basis (Ranta 1989, p.15), and is confirmed by several recent case studies (Kuivanen et al. 1988, Lakso 1988, Norros et al. 1988).

Denote the maximum theoretical number of minutes which machine j can operate per time period by T_{jMAX}. Then using the utilized time (T_j) and nonavailable time (T_{dj}) of machine j, the following expression holds:

$$T_j + T_{dj} \leq T_{jMAX} \qquad (j = 1,...,m) \qquad (11)$$

Since the left hand side of (11) is a measure of the utilization of machine j, we can impose a minimally acceptable utilization T_{jMIN}, so that (11) becomes (12),

$$T_{jMIN} \leq T_j + T_{dj} \leq T_{jMAX} \qquad (j = 1,...,m) \qquad (12)$$

Aggregating (12) over all machines we derive the systems level constraint (13),

$$TMIN \leq T + T_d \leq TMAX, \qquad (13)$$

where TMIN is the minimally acceptable utilization of the system, TMAX is the physical upper bound on the utilization time of all m machines, $T = \sum_{j=1}^{m} T_j$ is the total utilized time of all m machines combined, and $T_d = \sum_{j=1}^{m} T_{dj}$ is the total machine disturbance time. Note that while usually $TMAX = \sum_{j=1}^{m} T_{jMAX}$ holds, as it represents a physical limitation to the system, it is not necessarily true that $TMIN = \sum_{j=1}^{m} Tj_{MIN}$, because the appropriate value of this parameter is set by management.

Objectives

The general problem of the FMS design is to maximize the production volume within the system-dependent machine time constraints, while at the same time minimizing the costs and maximizing flexibility by possesing the ability to produce a diverse and complex part family, using as small a batch size as possible. These three important criteria are formulated in (14), (15) and (16):

$$\text{maximize PRODUCTION} = \sum_{i=1}^{n} b_i*v_i \qquad (14)$$

$$\text{minimize COST} = C \qquad (15)$$

$$\text{maximize FLEXIBILITY} = \sum_{i=1}^{n} f_{gi}*g_i*b_i*v_i + \sum_{i=1}^{n} f_{vi}*b_i*v_i - \sum_{i=1}^{n} f_{bi}*b_i \qquad (16)$$

The functional form (14) representing total production volume differs from Ranta and Alabian (1988) and Ranta (1989) where only the number of batches was included (PRODUCTION = $\sum_{i=1}^{n} v_i$). The formulation in (14) appears more appropriate. The cost function (15) has been introduced above (see (1), (3)-(8)). Flexibility in (16) is measured as a function of complexity, production volume and batch size, where the minus sign of the third term indicates that smaller batches are preferred. The coefficients f_{gi}, f_{vi} and f_{bi} are postitive scalar constants.

Depending on the decision maker's needs it is possible to refine and extend these criteria. For instance, one can assign relative importance weights to the production of different members of the part family. This may be appropriate if certain parts yield more valuable final products or realize higher contributions (as e.g. measured by profits) to the firm. Denoting the relative importance of part i by w_i, we can replace (14) by (14a),

$$\text{maximize W\_PRODUCTION} = \sum_{i=1}^{n} w_i*b_i*v_i \qquad (14a)$$

In many cases, however, maximizing a linear combination of the production volumes of individual parts (such as in (14a)) may not be appropriate or insightful. If the parts can be grouped into k disjoint more or less homogeneous groups, say $G_1,...,G_k$, such that $G_1 \cup ... \cup G_k = \{1,...,n\}$, then a useful approach would be to maximize the production volume of each group separately, implying the set of criteria in (14b):

$$\begin{aligned} &\text{maximize PRODUCTION\_1} = \sum_{i \in G_1} b_i*v_i \\ &\quad\vdots \qquad\qquad\qquad\qquad \vdots \\ &\text{maximize PRODUCTION\_k} = \sum_{i \in G_k} b_i*v_i \end{aligned} \qquad (14b)$$

Using this formulation it is possible to directly evaluate the tradeoffs between the production volumes in each group. It is clear that many of the above criteria are conflicting, and that the decision problem of evaluating their tradeoffs is a complicated one. In the next section, we illustrate how our interactive decision support system can assist management with this difficult task.

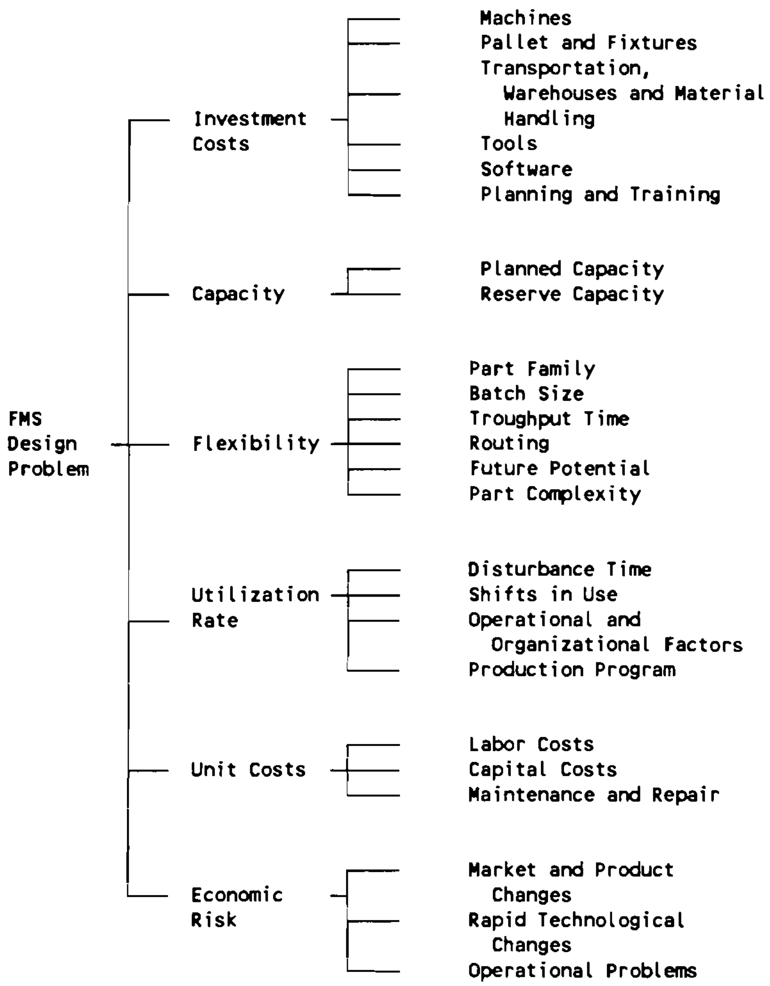
ILLUSTRATION

Our example is based on a real case. More specifically, the data have been collected by Ranta (Ranta and Alabian 1988) and are based on a real system in the Finnish metal product industry. For reasons on confidentiality the name of the company is not revealed. A few years ago this company went through a research and development phase, in which management conducted a series of interviews to pin-point problems in production. A subsidiary of the company produces gears for diesel engines, and it was decided to consider an FMS for this subsidiary. A section of the subsidiary producing 80 different parts is used to illustrate how our decision support framework can be applied in FMS pre-design stage.

Phase One

Suppose that initially we have 30 different feasible FMS designs. The major criteria used in pre-screening the alternatives are given in Figure 1. The FMS design problem has six global criteria: investment costs, capacity, flexibility, utilization rate, unit costs and economic risk. Each of these criteria is broken down into more detailed components. For instance, economic risk is divided into changes in the market, which may call for quick adjustments in the product line, technological change which may render the FMS design obsolete before the end of its planned lifetime, and operational problems related to overcapacity, for instance due to fluctuations in product demand. Even though this is not done in our illustration, the second level criteria can be refined as well. Software costs, for example, may relate to NC-programs and systems control, communication, scheduling, tool management and diagnostic software.

Figure 1: Hierarchical Tree of Criteria for Pre-Screening Candidate FMS Designs



Each of the criteria in Figure 1 is compared pairwise with the other criteria at the same level and branch, yielding a composite importance weight for each lowest level criterion. All of the 30 candidate FMS designs are separately rated on these criteria. Higher ratings are better, and each final rating is between zero and one. Table 1 shows a representative part of the results from the ratings process for the ten highest ranking alternatives. Noteworthy is that the categories of evaluation are quite general and qualitative. For instance, alternative 5 is judged as having "High" machine costs, and a "Average" adjustment to changing technology. From Table 1 it is clear that the top four FMS designs were considerably higher rated than the others. These four configurations were selected for a more detailed analysis in phase two.

Table 1: Pre-Screening Ratings of the Ten Highest Scoring FMS Designs

Alternatives	Criteria							Total
	Investment Costs			...	Economic Risk			
	Machines	Pallet and Fixtures	...		Market Adaptation	Technology Adjustment	Operations (Utilization)	Rating
1	Medium	Medium			Easy	Fast	Good	0.302
2	High	Low			Easy	Average	Good	0.283
3	High	Medium			Easy	Average	Excellent	0.265
4	Very High	Medium			Average	Fast	Average	0.212
5	High	Very High			Easy	Average	Average	0.196
6	Very High	High			Average	Fast	Good	0.166
7	Medium	Medium			Average	Average	Good	0.151
8	High	High			Average	Average	Poor	0.145
9	High	Medium			Average	Slow	Average	0.139
10	Medium	Low			Difficult	Fast	Average	0.127

Phase Two

We illustrate the phase two analysis using FMS design alternative 2 from the pre-screening phase. Without loss of generality we follow Ranta (1989) in selecting a representative group of 13 members from the original part family of 80. The data are identical to those used in the above study. The general model introduced above was simplified to the linear case along the lines suggested by Ranta and Alabian (1988), by solving the multicriteria problem for fixed batch sizes. In reality, of course batch sizes can freely be changed. Thus, in order to comprehensively evaluate the tradeoffs between the criteria, the analysis should be repeated for several different reasonable batch sizes.

The proposed FMS design consists of one turning machine, two machine centers, one grinding machine and automatic transportation and warehouses for system integration. Below we will discuss the analysis for the case where the batch size for each part is taken to be five. This batch size is relatively small, and as mentioned above for a complete analysis of the model dynamics other batch sizes are to be analyzed as well. The form of the constraints and criteria closely follows the general formulation in (1)-(16). All model parameters were calculated using equations (1) through (13). The transportation costs were not available in our case and were omitted from the cost equation (1). In addition to (1) - (13), lower and upper bounds were included for the production volume of each part. These are of the form (17),

$$V_{iMIN} \leq V_i \leq V_{iMAX} \qquad (i = 1,\ldots,13) \qquad (17)$$

The three criteria considered are to maximize the total production volume, to minimize investment costs and to maximize flexibility. These criteria are described in (14), (15), 16). For our particular application it has also deemed appropriate to include a factor related to the total number of batches in the machine time utilization equation (13). Thus, using a batch change time r_i for part i, we obtain the modified constraint (13a),

$$T_{MIN} \leq T + T_d + \sum_{i=1}^{n} r_i * v_i \leq T_{MAX} \qquad (13a)$$

The flexibility criterion in (16) was simplified to include the first term only. Tables 2 through 5 contain the relevant data. The first column of Table 2 provides an index for the parts, followed by minimum and maximum production volumes for each part in units per year (V_{iMIN}, V_{iMAX}), machining and overhead times (T_{ij} and t_{ij}), complexity coefficients g_i, batch change times T_{bi} and the number of tools needed in production,

L_i ($L_i = \sum_{j=1}^{4} l_{ij}$).

Table 2. Part family, maximum and minimum production boundaries, part complexity,tooling and overhead times, batch change times and numbers of tools needed in production

i	V_{iMIN}	V_{iMAX}	g_i	T_{i1}	t_{i1}	T_{i2}	t_{i2}	T_{i3}	t_{i3}	T_{i4}	t_{i4}	r_i	L_i
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 provides the disturbance (nonavailability) coefficients associated with equation (10) and the machine utilization bounds in (12). Note that a number of coefficients in this table have been aggregated, so that we do not have different values for each machine and each part, and the appropriate subscripts have been omitted. For instance, $d^b = \sum_{i=1}^{13} \sum_{j=1}^{4} d^b_{ij}$. The right-most column of Table 3 gives the maximum annual production time for each machine (316,800 minutes). No minimum production times were specified.

Table 3. Disturbance coefficients and time constraints

d^b	d^g	d^s	d^{PL}	s	PL	T_{jMAX}
3	40	0.05	3	1	100	316800

The cost coefficients are given in Table 4. As in Table 3, some of the coefficients are aggregate measures. In the model the coefficients in the third row of Table 4 were used. The efficiency of each machine as measured by average tooling speed is given in Table 5.

Table 4. Cost and flexibility coefficients

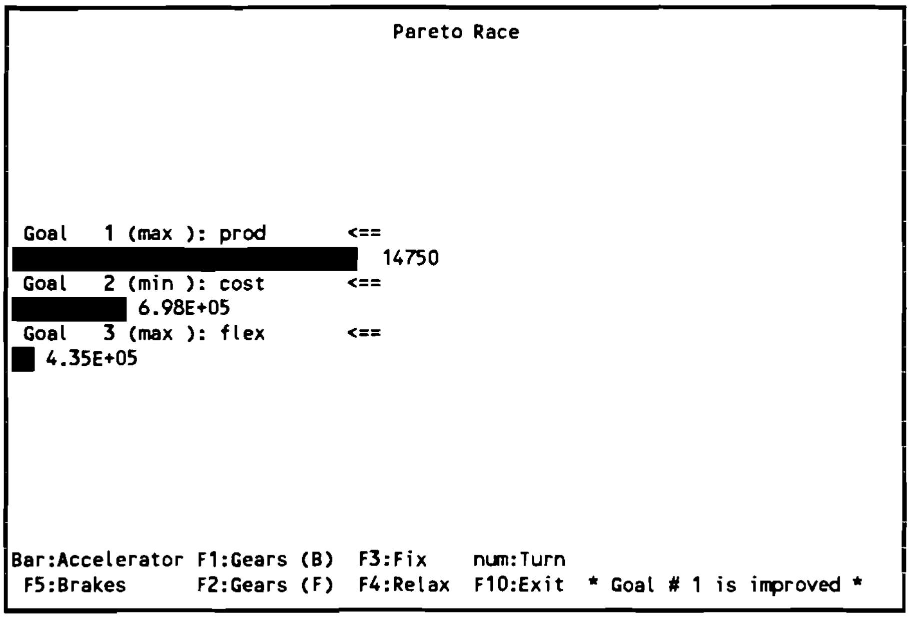
s_g	s	s_v	s_e	h	p_g	p_b	p_v	M	q_g	q	c_{PL}	f_g
0.5	10	20	2	3	10	3	200	100	5	10	100	10

Table 5. Efficiency coefficients

e_1	e_2	e_3	e_4
3	3	3	6

Next we demonstrate the interactive process using the VIG package (Korhonen 1987). The model is input using spreadsheets, after which the initial efficient solution is displayed in the visual mode as in Figure 2.

Figure 2. Initial Solution



In this solution, a total of 14,750 units are produced annualy, and an investment of $ 698,000.00 is required, while the flexibility measure is 435,000.00. In order to evaluate these figures relative to the range of possible outcomes, the utopia and nadir values (shown in Table 6) are calculated for each criterion. The utopia value for a criterion is the best possible outcome for this criterion, regardless of the other criteria. Since the different criteria are conflicting, the utopia values for all criteria combined can usually not attained. The nadir value for a criterion provides a bound for its worst possible efficient outcome. Thus, the decision maker cannot hope for a solution better than the utopia point, and will not be presented with solutions dominated by the nadir point.

Table 6. Utopia and Nadir Values for the Criteria

Criterion	Utopia Value	Nadir Value
Production Volume	17447.50	14750.00
Costs	697998.50	822135.77
Flexibility	523723.08	435000.00

Given the initial solution, the decision maker can freely choose which goal(s) or criteria he wants to improve. Of course this means that he has to sacrifice the values of some other criteria at the same time. Suppose the decision maker is willing to accept higher investment costs in exchange for a higher flexibility and a larger production volume. After indicating the appropriate goal directions by manipulating the arrows on the screen (see Figure 2), the decision maker follows the reference direction generated by the computer program. In our case, the flexibility and production criteria are emphasized, and the program projects the reference direction on the efficient frontier. We continue moving in this direction until we hit the boundaries of the efficient set. If it is still possible to improve the criterion values, the program generates a new reference direction and we can continue to improve the production and flexibility criteria. Troughout this process, the changing criterion values are visually displayed on the screen as expanding or shrinking bar graphs.

Let us assume the decision maker wishes to change the search direction after reaching the solution shown in Figure 3, where production volume equals 16,733.40 units, the investment costs are $789,000, and the flexibility is 503,000. Suppose he is satisfied with the level of flexibility, but does not want to accept values worse than the current level of 503,000. At the same time, he is willing to exchange some production volume in order to decrease the investment costs. Thus, the flexibility goal is fixed at its current level (as indicated by the star at the left of this goal in Figure 4), and the emphasis on improving the cost criterion is indicated by changing the direction of the arrows for the cost goal on the screen.

Figure 3. Fixing one goal

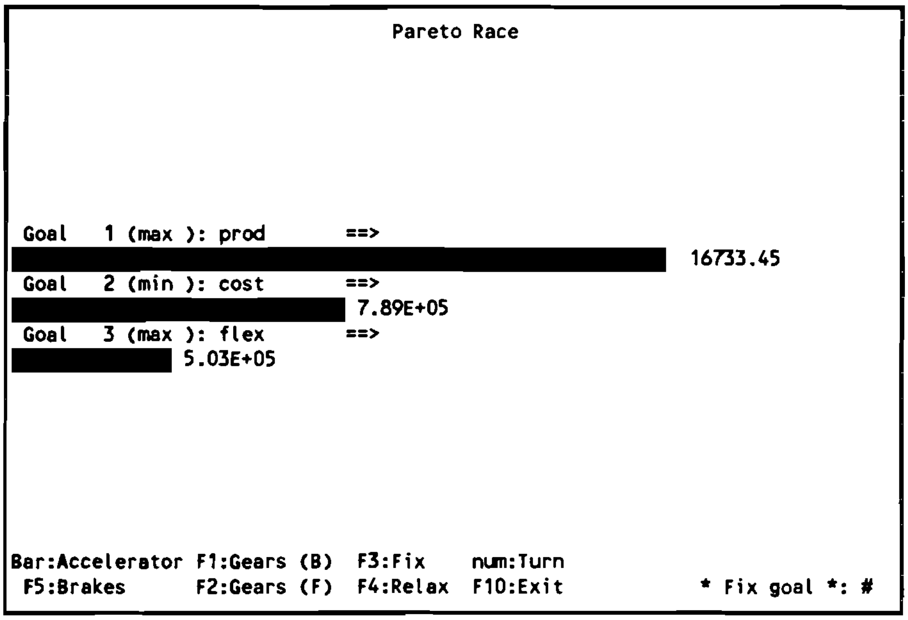
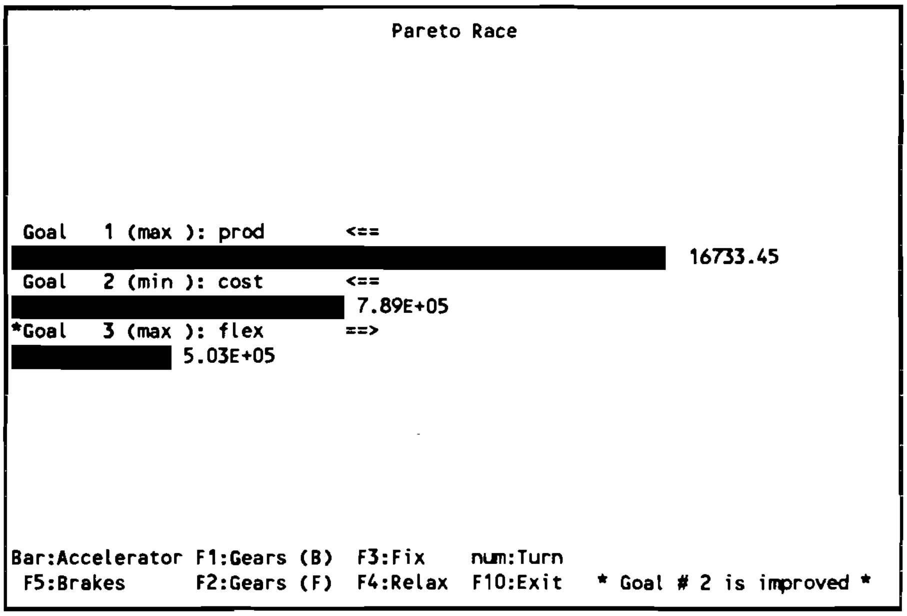


Figure 4. Changing the search direction



The resulting reference direction, where both the cost goal and the production goal are decreasing is shown in Figure 5, so that production volume sacrificed in exchange for lower investment costs. The decision maker can continue to play with VIG as long as he wishes, and stop as soon as he has reached a solution with which he is satisfied. In our illustration we stopped after reaching the solution given in Figure 5, where production volume, costs and flexibility are 16,498.90 units, $ 778,000 and 503,000, respectively. Note that the flexibility value in the final solution in identical to Figure 4, because this goal was fixed.

Because the actions on the part of the decision maker are similar to driving a car (VIG has gears, breaks and an accellerator), the search for the "most prefered" solution is also called a "Pareto Race" (Korhonen and Wallenius 1988). If he so desires the decision maker can inspect the values of the decision variables, in our case the batch sizes and number of batches produced, at any point during the solution process. The values of the criteria and decision variables for the final solution are given in Figure 6.

Figure 5. The final solution

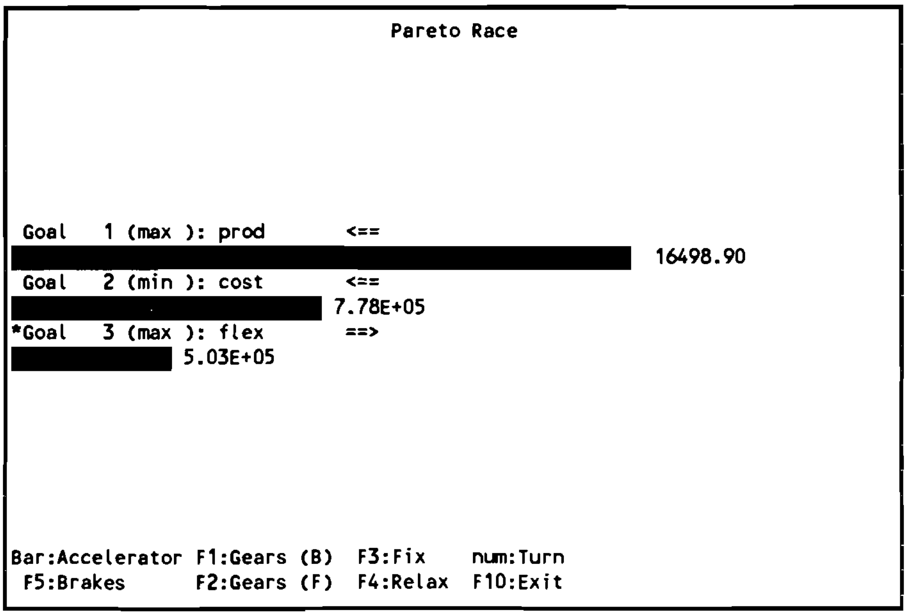


Figure 6. Values of Criteria and Decision Variables for the Final Solution

Names	Current Values
PRODUCTION	16498.90
COST	778448.85
FLEXIBILITY	502563.82
T_1	316800.00
T_2	218943.25
T_3	232993.25
T_4	195345.40
Eq.(13a)	1014857.30
td	2380.05
v_1	140.00
v_2	500.00
v_3	400.00
v_4	321.67
v_5	209.68
v_6	60.00
v_7	60.00
v_8	600.00
v_9	600.00
v_{10}	300.00
v_{11}	58.43
v_{12}	30.00
v_{13}	20.00

EXTENSIONS

As mentioned above, our model can be extended in a number of different ways. For example, Ranta and Alabian (1988) and Ranta (1989) suggest several viable additional criteria, including relative performance indicators such as the average machine time per part (T_M), average throughput time (T_U), i.e. the average time to produce a part, and unit time cost (K), i.e. the total discounted cost per period divided by the total production time per period. These criteria can be represented by (18) - (20).

$$\text{minimize } T_M = T / \sum_{i=1}^{n} b_i * v_i \tag{18}$$

$$\text{minimize } T_U = (T + \sum_{i=1}^{n} r_i * v_i + T_d) / \sum_{i=1}^{n} b_i * v_i \tag{19}$$

$$\text{minimize } K = (C + L) / (T) \tag{20}$$

where r_i is the batch change time for part i and L is the discounted labor, maintenance and improvement cost of the system per period.

Another issue is that even though linear relationships are often reasonably good approximations of the true model, in some cases a nonlinear formulation is preferred. In the general model described above, the nonlinearities relate to the batch size and number of batches of each part. Other nonlinearities which may significantly improve the model may include nonlinear cost relationships and nonlinear functions describing flexibility.

As mentioned above, the illustration example was simplified to the linear case for ease of presentation. Since the VIG package is restricted to linear models, other software should be used if it is deemed necessary to introduce nonlinearities. One good candidate is the menu-driven and computationally powerful package IAC-DIDAS-N (Kreglewski et al. 1988). This package was designed to solve nonlinear multicriteria problems, and runs on IBM-PC/XT and compatible machines. Currently the authors are experimenting with various nonlinear refinements and extensions of the FMS design problem using the IAC-DIDAS-N package. The results of these experiments, and the comparison of the results with those obtained using linear models will be reported in a future paper.

CONCLUSIONS

In this paper a user friendly visual interactive decision support system is introduced which aids management in the strategic investment decision problem of which FMS configuration to acquire. The system can be used both in the initial pre-screening of alternative candidate FMS designs and in the more detailed performance analysis of a select group of most attractive candidate designs. As such, the methodology can play an important role in the pre-design phase of building an FMS.

Our methodology contributes to the current literature in that it facilitates the difficult and complicated process of evaluating various types of tradeoffs between multiple, potentially conflicting criteria. Both quantitative and qualitative criteria are explicitly considered in the decision process. A simple example based on a case study with real data was used to illustrate the concepts. The particular software packages used (Expert Choice and VIG) are commercially available and have been proven to be very appealing to users in numerous real life applications. Future research should focus on nonlinear refinements of the current model. The scope of the model should be extended as well, including more detailed information about various cost components and more accurate measures of flexibility and part complexity.

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APPENDIX 1

Concise list of equations used in the paper:

$$C = C_M + C_L + C_P + C_S + C_T + C_O \qquad (1)$$

$$C_M = \sum_{j=1}^{m} e_j * M_j, \qquad (2)$$

$$e_j = \sum_{i=1}^{n} e_{ij} * b_i * v_i * (T_{ij} + t_{ij}) \qquad (j = 1,...,m) \qquad (3)$$

$$C_L = \sum_{i=1}^{n} q_{gi} * g_i + \sum_{i=1}^{n} \sum_{j=1}^{m} q_{ij} * l_{ij}, \qquad (4)$$

$$C_P = \sum_{i=1}^{n} p_{gi} * g_i + \sum_{i=1}^{n} p_{bi} * b_i + \sum_{i=1}^{n} p_{vi} * v_i, \qquad (5)$$

$$C_S = \sum_{i=1}^{n} s_{gi} * g_i + \sum_{i=1}^{n} (s + s_{vi}) * v_i + \sum_{i=1}^{n} \sum_{j=1}^{m} h_{ij} * l_{ij} + \sum_{j=1}^{m} s_{ej} * e_j, \qquad (6)$$

$$C_T = u * V + \sum_{i=1}^{n} u_i * g_i + \sum_{i=1}^{n} u_{vi} * v_i, \qquad (7)$$

$$C_O = C_{TR} + C_{RES} \qquad (8)$$

$$T_j = \sum_{i=1}^{n} (T_{ij} + t_{ij}) * b_i * v_i, \qquad (j = 1,...,m) \qquad (9)$$

$$T_{dj} = \sum_{i=1}^{n} d^g{}_{ij} * g_i + \sum_{i=1}^{n} d^b{}_{ij} * v_i + d^s{}_j * S_j - d_j{}^{PL} * PL \qquad (j = 1,...,m) \qquad (10)$$

$$T_j + T_{dj} \le T_{jMAX} \qquad (j = 1,...,m) \qquad (11)$$

$$T_{jMIN} \le T_j + T_{dj} \le T_{jMAX} \qquad (j = 1,...,m) \qquad (12)$$

$$TMIN \le T + T_d \le TMAX, \qquad (13)$$

$$TMIN \leq T + T_d + \sum_{i=1}^{13} r_i * v_i \leq TMAX \qquad (13a)$$

$$\text{maximize} \quad PRODUCTION = \sum_{i=1}^{n} b_i * v_i \qquad (14)$$

$$\text{maximize} \quad W\_PRODUCTION = \sum_{i=1}^{n} w_i * b_i * v_i \qquad (14a)$$

$$\text{maximize} \quad PRODUCTION\_1 = \sum_{i \in G_1} b_i * v_i$$

$$\vdots \qquad\qquad \vdots \qquad (14b)$$

$$\text{maximize} \quad PRODUCTION\_k = \sum_{i \in G_k} b_i * v_i$$

$$\text{minimize} \quad COST = C \qquad (15)$$

$$\text{maximize} \quad FLEXIBILITY = \sum_{i=1}^{n} f_{gi} * g_i * b_i * v_i + \sum_{i=1}^{n} f_{vi} * b_i * v_i - \sum_{i=1}^{n} f_{bi} * b_i \qquad (16)$$

$$V_{iMIN} \leq V_i \leq V_{iMAX} \qquad (i=1,\ldots,13) \qquad (17)$$

$$\text{minimize} \quad T_M = T \,/\, \sum_{i=1}^{n} b_i * v_i \qquad (18)$$

$$\text{minimize} \quad T_U = (T + \sum_{i=1}^{n} r_i * v_i + T_d) \,/\, \sum_{i=1}^{n} b_i * v_i \qquad (19)$$

$$\text{minimize} \quad K = (C + L) \,/\, (T) \qquad (20)$$

APPENDIX 2

Concise list of decision variables and model parameters used in the paper:

Decision Variables:	Description:
b_i	batch size, part i
v_i	number of batches produced per period, part i

Indices:	Description:
$i \in \{1,...,n\}$	the set of parts
$j \in \{1,...,m\}$	the set of machines

Model Parameters:	Description:
c_{PL}	training costs per employee per period
e_{ij}	efficiency of machine j on part i
e_j	efficiency of machine j
g_i	measure of complexity of part i
l_{ij}	number of tools needed on machine j to produce part i
M_j	direct investment costs per unit produced per period, machine j
PL	number of employees to be trained per period
S_j	complexity of the software needed for machine j
T_{ij}	unit tooling time of part i on machine j
t_{ij}	unit overhead time of part i on machine j
T_{jMAX}	maximum minutes machine j can operate per period
T_{jMIN}	required minimum minutes machine j should operate per period
T_{MAX}	maximum minutes all machines combined can operate per period
T_{MIN}	required minimum minutes all machines combined should operate per period
T_j	total time machine j is in operation per period
T_{dj}	total nonavailable (disturbance) time of machine j per period
T	total time all machines combinede are in operation per period
T_d	total nonavailable (disturbance) of all machines combined per period
V_i	production quantity of part i per period
V	total production capacity per period
w_i	relative importance weight of producing part i
y	planed lifetime of the system
L	discounted labor, maintenance and improvement costs per period of the system
r_i	unit batch change time for part i

Scaling Coefficients for Contribution to

Model Parameters:	**Description:**
d^g_{ij}	nonavailability of complexity of part i produced on machine j
d^b_{ij}	nonavailability of batch size of part i produced on machine j
d^s_j	nonavailability of software size and complexity for machine j
d^{PL}_{ij}	nonavailability of personal training for part i on machine j
q_{ij}	total costs of number of tools needed, l_{ij}
q_{gi}	tool costs of complexity of part i
p_{gi}	parts pallets costs of complexity of part i
p_{bi}	parts pallets costs of batch size of part i
p_{vi}	parts pallets costs of number of batches produced of part i
h_{ij}	software costs of number of tools needed, l_{ij}
s_{gi}	software costs of complexity of part i
s	software costs of total number of batches produced
s_{vi}	software costs of number of batches produced of part i
s_{ej}	software costs of efficiency of machine j
u	transportation costs of total production capacity
u_i	transportation costs of complexity of part i
u_{vi}	transportation costs of number of batches produced of part i
f_{gi}	flexibility of complexity of part i
f_{vi}	flexibility of production volume of part i
f_{bi}	flexibility of batch size of part i

Cost Component:	**Description:**
C_M	machine costs per period
C_L	tool costs per period
C_P	parts pallet costs per period
C_S	software costs per period
C_T	transportation costs per period
C_O	other costs per period

APPENDIX 3

Concise list of the criteria used in the paper:

Criteria:		Description:
Maximize	PRODUCTION	total production volume of the system per period
Minimize	COST	total direct investment cost of the system per period
Maximize	FLEXIBILITY	total flexibility of the system
Maximize	W_PRODUCTION	total weighted production of the system per period
Maximize	PRODUCTION_J	production volume of part group j per period
Minimize	T_M	average machine time per part
Minimize	T_U	average throughput time
Minimize	K	unit time cost