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A multiple-criteria approach to machine selection for flexible manufacturing systems*

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Abstract

This paper describes *a visual interactive decision support framework* designed to aid decision makers in selecting the most appropriate machines for a flexible manufacturing system (FMS). The framework can be used in *the preinvestment stage of the planning process, after a decision has been made, in principle, to build an FMS.* The framework mainly consists of two parts. The first part is called the *prescreening stage*, which narrows down all possible configurations by using the analytic hierarchy process (AHP). The second part uses a goal programming (GP) model to find out the satisfactory candidate from the remaining shortlisted configuration. After applying the GP model, AHP is used again for sensitivity analysis. This approach helps managers explore and evaluate costs and benefits of various scenarios for each configuration separately by experimenting with different types of machines and degrees of flexibility of the system.

1. Introduction

The shortening of product life cycles and the fierce competition in the market have made manufacturers increasingly wary of the types of manufacturing system technologies and thus they must establish so as to maintain a competitive edge for long-term survival. In recent years, the flexible manufacturing system (FMS) has been widely considered as an effective instrument toward this end. However, implementing an FMS is very costly, and this investment tends to be irreversible, thus necessarily requiring careful consideration before a decision can be made. Decision-making concerning the implementation of an FMS is not only strategic but also involves issues at the tactical and operational levels. The decision situation is characterized by the presence of both qualitative and quantitative criteria involving social and economic factors. In view of the multiplicity of criteria inherent in such decision-making situations, the methodology of multiple-criteria decision making (MCDM) is used as the framework of analysis.

Several authors have studied machine selection in the FMS. Among them are Frazelle [1], Miltenburg and Krinsky [2], Amit and Ilan [3] and Stam and Kuula [4]. Some examples are presented in [5]. Krinsky and Miltenburg [2] and Amit and Ilan [3] proposed a two-phase model for selecting from among a number of FMSs by considering risk analysis. Stam and Kuula [4] used AHP and goal programming methods to select the best and optimal system for a particular manufacturing situation. However, they did not take into account the case of unstable demand situation, risk and the effect of flexibility.

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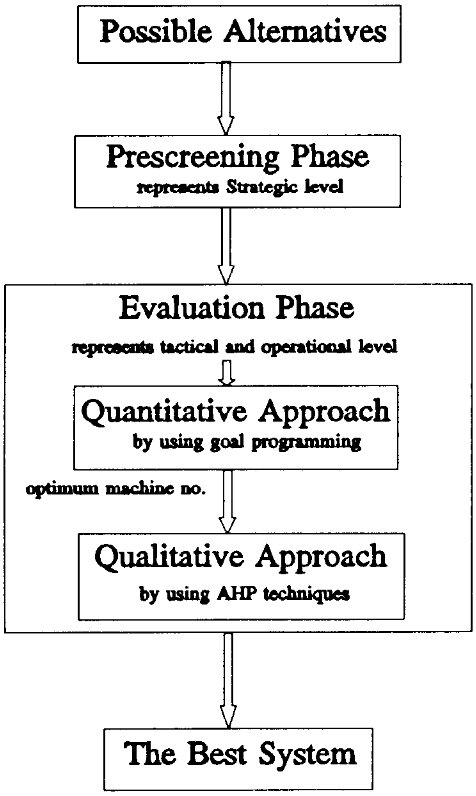

Fig. 1. Overall procedure of the model.

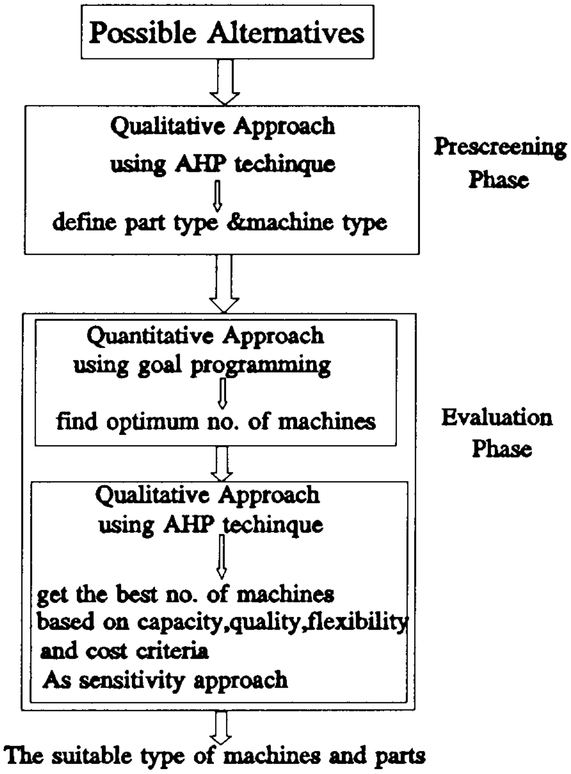

Fig. 2. Data flow diagram of the model.

The model framework in this paper is similar to that used by Stam and Kuula [4] in the sense that AHP and GP, as specific techniques in MCDM, are used . It also takes some interesting features of the model developed by Krinsky and Miltenburg [6] and incorporates the flexibility aspect of the system. The decision framework as proposed in this paper, is made up of two phases, namely the prescreening phase – strategic approach – and the evaluation phase – tactical approach. The overall methodology is depicted in Fig. 1 and the data flow diagram is presented in Fig. 2. Both figures consider both quantitative and qualitative criteria.

2. Model development: Phase I

As shown in Fig. 2, the model has two main parts: the prescreening phase and the evaluation phase.

2.1. *Prescreening phase*

The prescreening phase mainly considers the strategic level. At this level, there is a set of plans and policies by which manufacturing seeks to consider – cost, performance, quality, delivery, flexibility and innovativeness. Moreover, strategic analysis consists of aspiring for two things, i.e. the proposed alternatives should be consistent with the overall manufacturing strategy and the organization should have the ability to exploit the new system successfully. At the first level, the types of products are classified according to four different characteristics as follows.

(1) *Introductory demand situation*: The products are planned to be produced with the new system.

(2) *Increasing demand situation*: The products have already been produced with the existing system and introduced in the market,

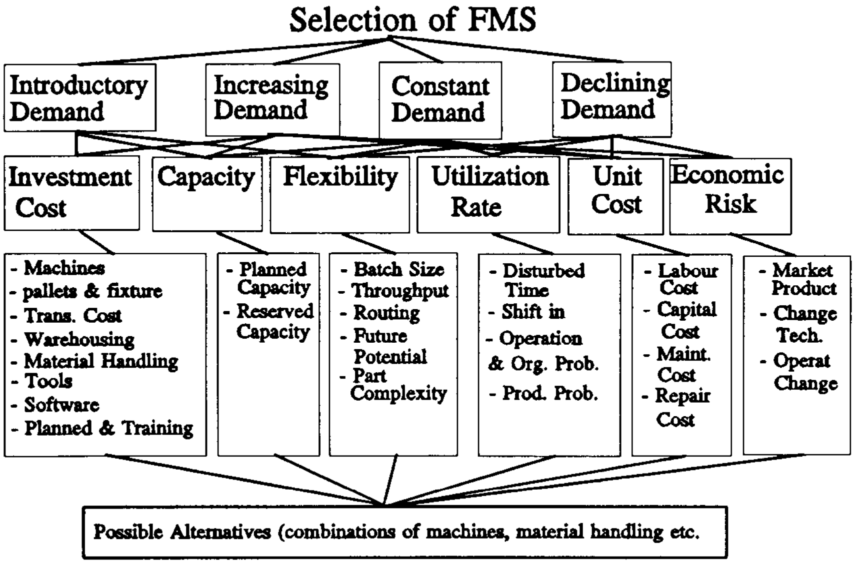

Fig. 3. Hierarchical structure of the decision problem.

and the present demand condition is high with high fluctuation.

(3) *Constant demand situation*: The products have already been produced with the existing system, and market demand is constant and stable.

(4) *Declining demand situation*: The products have already been produced with the existing system, and demand is declining with stable condition, but is still considered profitable.

The criteria considered are investment cost, capacity, flexibility, utilization rate, unit cost and economic risk. After defining the criteria, it is necessary to define the possible alternatives which depends solely on the specific situation and the type of products planned to be produced with the selected system. The main alternatives are the various combinations of the types of machines, material handling system and computers. Accordingly, the overall diagram of the first-phase model is shown in Fig. 3.

3. Evaluation phase

The results obtained from the prescreening model are taken into the evaluation phase, which aims to evaluate the system using quantitative and qualitative criteria. The evaluation phase is mainly divided into two parts. The first employs a quantitative approach to find the best number of units of each type of machines already selected from the prescreening phase. The other is to find out the sensitivity of the results using qualitative criteria by changing the types of machines and the best numbers of machines obtained from the quantitative criteria analysis.

3.1. Quantitative criteria analysis – The goal programming model

In the evaluation phase, a goal programming model is developed for selecting the number of machines required for multigoal consideration. The weights of each goal representing the designer preference are taken into consideration. The validity of the model is based upon the following assumptions:

(1) Each product type's set of operations is known and has a prespecified production goal.

(2) Operations are defined by the tools and machine characteristics. Thus, operational time is dependent on the type of machines.

(3) Each type of part requires one type of pallet and fixture.

(4) The total number of pallets equals three times the number of machines in the system [7].

The requirement is to find the number of each type of machines and pallets according to the corresponding demand characteristic of products to obtain maximum profit. The system constraints can be developed as follows.

(1) Total number of machines,

$$\sum_{j=1}^{J} C_j \leqslant \mathrm{LNM}, \tag{1}$$

where LNM is the limited total number of machines and C_j is the number of machines of type j.

(2) All products are planned to be produced:

$$N_i \geqslant 1, \quad i = 1, \ldots, I, \tag{2}$$

where N_i is the number of products of type i to be produced.

(3) According to operation constraints, each type of machines must be purchased:

$$C_j \geqslant 1, \quad j = 1, \ldots, J. \tag{3}$$

(4) Machine capacity:

$$\sum_{k=1}^{K} \sum_{i=1}^{I} N_i N_{ki} t_{kj} \leqslant \mathrm{MC}_j * C_j, \quad j = 1, \ldots, J, \tag{4}$$

where N is the number of parts k to form product i, MC_j is the type j machine capacity and t_{kj} is the time required to machine part k at machine type j.

(5) Fixture capacity: Fixtures play an important role in an FMS because they are used to hold, locate and align parts while they are machined or transported. Since there are a limited number of fixtures for each part type in the system, the total fixture using time for each part should not exceed the total available time of the corresponding fixtures.

$$\sum_{j=1}^{J} (t_{kj} + \mathrm{FT}_{kj}) \sum_{i=1}^{I} N_i N_{ki} \leqslant \mathrm{FAT}_k F_k, \quad k = 1, 2, \ldots, K, \tag{5}$$

where FT_{kj} is the fixture time for part k at machine type i, FAT_k is the available time of fixture k and F_k is the number of fixture types k.

(6) Material handling system: In an FMS, the material handling system is an essential element in order to achieve flexibility and, therefore, it is necessary to include it in the system constraints. In general, there are two types of material handling systems, namely conveyors (continuous type) and automatic guided vehicles (AGV) (discrete type).

The limitations on conveyor length are the main point of concern:

$$\sum_{j=1}^{J} (C_j * S_j + \mathrm{DM}_j) + \mathrm{ABC} \leqslant \mathrm{BL}, \tag{6a}$$

where DM_j is the distance between the preceding machine type j, S_j is the size of type j machine, ABC is the additional length of the belt and BL is the limited belt length.

$$\sum_{k=1}^{K} \frac{F_k}{\mathrm{NG}_k} \leqslant \mathrm{NAGV}, \tag{6b}$$

where F_k is the available time for fixture type k, NG_k is the total available number of pallets and NAGV is the total number of AGVs.

(7) Computer control utilization: Computers are an integral part of an FMS. There are two types of computer resource constraints. One is the main host computer and the other is the computer in each machine.

For the host computer,

$$\sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{i=1}^{I} N_i N_{ki} C_j \mathrm{ME}_{kj} \leqslant \mathrm{TMCH} * \mathrm{THC}, \tag{7a}$$

where ME_{kj} is the memory required for part type k at machine j, TMCH is the total memory available at the computer and THC is the number of host computers.

For the computer in each machine,

$$\sum_{k=1}^{K} \sum_{i=1}^{I} N_i N_{ki} \mathrm{ME}_{kj} \leqslant \mathrm{TNC}_j * \mathrm{TME}_j, \quad j = 1, \ldots, J, \tag{7b}$$

where TNC_j is the total number of computers in type j machine and TME_j is the total memory available at type j machine.

(8) Tools: Machine tool constraints are also basic constraints in the machine and can be expressed as

$$\sum_{k=1}^{K} \sum_{i=1}^{I} N_i N_{ki} (t_{kj} + \mathrm{TS}_{kj}) \leqslant \mathrm{TOL}_j \mathrm{MC}_j, \quad j = 1, 2, \ldots, I, \tag{8}$$

where TS_{kj} is the additional tool handling time, TOL_j is the total available time of tools at machine j and MC_j is the tool capacity at machine type j.

The goals considered are as follows:

(1) Maximize profit to cover the cost of automation
(2) To minimize the cost of investment, it is needed to minimize the total number of pallets, fixtures and AGV.
(3) To fulfil the demand of products.
(4) Balancing loading in machines.

After defining the goals of the system, the goal constraints can be formulated as follows.

(A) Profit:

$$\sum_{i=1}^{I} B_i N_i - \sum_{j=1}^{J} \mathrm{MCC}_j \mathrm{NM}_j - \mathrm{AC} * \mathrm{NAGV} - \mathrm{CC} * (\mathrm{TNC}_j + \mathrm{THC}) - \mathrm{CL} * \mathrm{BL} - \sum_{j=1}^{J} \mathrm{TOL}_j * \mathrm{TTC}_j + \mathrm{d}r^- \mathrm{d}r^+ = T, \quad i = 1, 2, \ldots, I, \tag{9}$$

where B_i is the expected profit from product i, T the target profit, TTC_j the tool cost at type j machine, AC the AGV cost, MCC_j the type j machine cost, CC the computer cost and CL the belt cost.

(B) Total number of fixtures: To minimize the cost of production, the total number of fixtures should be minimized:

$$\sum_{k=1}^{K} F_k + \mathrm{d}c^- - \mathrm{d}c^+ = \mathrm{NPP}, \tag{10}$$

where NPP is the total number of available pallets.

(c) Demand:

$$\sum_{k=1}^{K} N_i N_{ki} + \mathrm{d}_i^- - \mathrm{d}_i^+ = D_i \quad i = 1, 2, \ldots, I, \tag{11}$$

where D_i is the demand of product type i.

(D) Machine loading: Minimize the overloading and underloading of machine capacity in each type of machine:

$$\sum_{k=1}^{K} \sum_{i=1}^{I} N_{ki} t_{kj} + \mathrm{d}m_j^- - \mathrm{d}m_j^+ = \mathrm{MC}_j * C_j, \quad j = 1, \ldots, J, \tag{12}$$

where MC_j is the type j machine capacity.

The goal objectives are proposed in the following order of priority:

Priority 1: Maximize profit.
Priority 2: Minimize the number of fixtures and pallets in the system.
Priority 3: Maximize production to satisfy demand.
Priority 4: Minimize overloading and underloading of machine capacity.

Then the overall objective goal can be presented as

$$\min \left[P_1 \mathrm{d}r^- + P_2 \mathrm{d}c_i^+ + P_3 \sum_{i=1}^{I} \mathrm{d}_i^- + P_4 \sum_{j=1}^{I} \mathrm{d}m_j^- + \mathrm{d}m_j^+ \right]. \tag{13}$$

3.2. Qualitative criteria – AHP approach for sensitivity analysis

After making quantitative parameter considerations, the AHP technique is used for sensitivity analysis. Under the AHP model, four main criteria are used – capacity, flexibility, quality and economic consideration. For each criterion, we used the following techniques.

3.2.1. Capacity criterion

For the capacity criterion, we used the closed queueing model (CQM) adapted from Shalev–Oren et al. [8] and made modifications on the consideration of machine failure as a failure customer. The arrival of the failure customer follows a Poisson distribution. To make the model more realistic by considering machine failure, the following assumptions should be made:

(1) Queue of breakdown is not permissible. This means that when a failure customer arrives at the station, the arrival of failure corresponding to that station is cut off.

(2) Failure distribution followed the Poisson process with rate λ.

(3) The service time for the failure customer arriving at the station is equal to the mean repair time of that machine and follows an exponential distribution with rate μ.

(4) The arrival of the failure customer is preempted by other customers until the machine is repaired.

(5) The closed failure customer chains are mutually exclusive. In other words, a failure customer associated with resource m and pure delay station m does not visit other resources or stations.

(6) The marginal queue length distributions of the preemptive failure customer classes are independent. Thus, the exactness of the marginal queue length distribution of the failure classes is preserved for each resource m in the network.

After stating the above assumptions, we can develop the following equation for mean waiting time due to the preemptive failure customer arrival situation:

$$R(m, p) = R1(m, p) + R2(m, p), \tag{14}$$

with

$$R1(m, p) = \frac{[T(m, p) + W(m, p) + L_m r_m]}{1 - \lambda_m O_m r_m},$$

$$R2(m, p) =$$

$$\frac{T(M + 1, p) + W(M + 1, p) + L_{M+1} r_{M+1}}{1 - \lambda_{M+1} O_{M+1} r_{M+1}}$$

where $T(m, p)$ is the mean machine time of part p in the machine group m for each visit to machine group m for $m = 1, 2, \ldots, M$, $W(m, p)$ is the mean waiting time of part p at machine group m due to other stations and parts including machine failure, $L_m r_m$ is the average number of failures observed by a job p on arrival to resource m, λ_m is the frequency of machine group m failure, $M + 1$ is the transportation station and O_m is the number of machines active in machine group m.

The algorithm can be developed as follows.

(1) Initialize: $W(m, p) = 0$; $m = 1, 2, \ldots, M + 1$, $p = 1, 2, \ldots, P$.

(2) Looping:

$$R1(m, p) = \frac{[T(m, p) + W(m, p) + L_m r_m]}{1 - \lambda_m O_m r_m},$$

$$R2(m, p) =$$

$$\frac{T(M + 1, p) + W(M + 1, p) + L_{M+1} r_{M+1}}{1 - \lambda_{M+1} O_{M+1} r_{M+1}},$$

$$X(m, p) = \frac{P(m, p) N(p)}{\sum_{t=1}^{M} P(t, p) R(t, p)};$$

for a single server,

$$W_0(m, p) = \sum_{t=1}^{P} [X(m, r)T^2(m, t)] - \frac{X(m, p)T^2(m, p)}{N(p)},$$

for a multiserver,

$$W_0(m, p) = B(m, p)DT(m, p),$$

where

$$B(m, p) = \frac{U(m, p)^{n(m)}(1 - XA(m, p)^{(V(m)-n(m)+1)})}{n(m)!(1 - XA(m, p))\left[\sum_{t=0}^{n(m)-1} \frac{U^2(m, p)}{t!}\right.} \left. + \frac{U^{n(m)}(m, p)(1 - XA^{V(m)-n(m)+1}(m, p)}{n(m)!\,(1 - XA(m, p))}\right]$$

if $V(m) \geqslant n(m)$,

$$U(m, p) = \sum_{t=1}^{P} X(m, t)T(m, t) - \frac{X(m, p)T(m, p)}{N(p)},$$

$$XA(m, p) = \frac{U(m, p)}{n(m)},$$

$B(m, p) = 0$ if $V(m) < n(m)$,

$$X(m, p) = \frac{P(m, p)N(p)}{\sum_{t=1}^{M} P(t, p)[W(t, p) + T(t, p) + T(M + 1, p) + W(M + 1, p)]}.$$

(3) Calculate

$$W(m, p) = W_0(m, p) + \frac{1}{n(m)}\left[\sum_{t=1}^{P} X(m, t)W(m, t)\mathrm{T}(m, t) - \frac{X(m, p)W(m, p)T(m, p)}{N(p)}\right],$$

$\mathrm{Wnew}(m, p) = W(m, p)$.

(4) Test:
If $(\mathrm{Wnew}(m, p) - (W(m. p)) \leqslant$ error for $m = 1, 2, \ldots, M + 1$ goto step 5: Output, else $W(m, p) = \mathrm{Wnew}(m, p)$ for $m = 1, 2, \ldots, M + 1$ go to step 2: Looping.

(5) Out put:
$U(m, p) = T(m, p)X(m, p)/n(m)$ for $m = 1, 2, \ldots, M + 1$,
$Q(m, p) = X(m, p)W(m, p)$ for $m = 1, 2, \ldots, M + 1$
for $p = 1, 2, \ldots, P$ $X(L/UL, p)$,

$$U(m) = \sum_{p=1}^{P} U(m, p), \qquad Q(m) = \sum_{p=1}^{P} Q(m, p).$$

Print
$\mathrm{U}(m)$ = utilization of machine m,
$Q(m)$ = mean number of parts queueing at station m.

Based on the above algorithm, a Pascal program is developed to determine the capacity of the system and the program listing is found in [9].

3.2.2. Flexibility criterion

For a flexibility criterion, some concepts of flexibility from Venk [10] and Chung and Chen [11] were adapted and the total flexibility index was developed as follows:

total flexibility index of the system

$$= \alpha Q + (1 - \alpha)E, \tag{15}$$

where α is the weight (designer's preference), Q is the normalized factor of quick response – measured with time – and E is the normalized factor of economic response to change – measured in cost.

In the evaluation model, the total flexibility index can be defined with hierarchical structure in Figs. 4 and 5. According to the above situation, it is necessary to define the flexibility index from the point of view of both cost and time. Therefore, it can be defined as follows.

(1) Defining pure component machine flexibility (Fmp(i) and Fmt(i)):

$$\mathrm{Fmp}(i)=\frac{C(i)}{\max[C(1),C(2),\ldots,C(M)]},$$

$$\mathrm{Fmt}(i)=\frac{\mathrm{Op}(i)}{\min[\mathrm{Op}(1),\mathrm{Op}(2),\ldots,\mathrm{Op}(M)]},$$

where $C(i)$ is the maximum cost added by machine i to part family, Fmp(i) is the machine flexibility (pure component) for machine type i and Op(i) is the minimum operation time spent at machine type i.

(2) Defining the overall and pure component part family flexibility index (Fdo(i,j), Fdp(i,j), Fpt(i,j) and Fpf(i,j)):

$$\mathrm{Fdp}(i,j)=\frac{C(i)/S(i,j)}{\max\left[\dfrac{C(1)}{S(1,1)},\dfrac{C(2)}{S(2,2)},\ldots,\dfrac{C(i)}{S(i,j)}\right]},$$

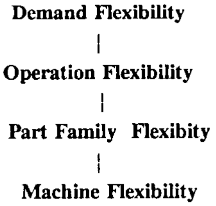

Fig. 4. Structure of flexibility index.

$$\mathrm{Fdo}(i,j)=\mathrm{Fdp}(i,j)\mathrm{Fmp}(j),$$

$$\mathrm{Fpt}(i,j)=\frac{\left[1-\dfrac{S(i,j)}{O(j)}\right]}{\max\left[\left(1-\dfrac{S(1,1)}{O(1)}\right),\left(1-\dfrac{S(2,2)}{O(2)}\right),\ldots,\left(1-\dfrac{S(i,j)}{O(M)}\right)\right]},$$

$$\mathrm{Fpf}(i,j)=\mathrm{Fmt}(i,j)*\mathrm{Fpt}(j),$$

where $S(i,j)$ is the total additional setup time required for part i encountered by machine type j and $O(j)$ is the minimum operation time required for part i on machine j.

(3) Defining the overall and pure component process flexibility index (Fpo(i,j,l) Fpp(i,j,l), Fppt(i,j,l) and Fpot(i,j,l)):

$$\mathrm{Fpp}(i,j,l)=\frac{[P(j,l)-C(i)]}{C(i)},$$

$$\mathrm{Fpo}(i,j,l)=\mathrm{Fpp}(i,j,l)*\mathrm{Fdo}(i,j),$$

$$\mathrm{Fpp}(i,j,l)=\frac{\dfrac{(T(j,l)-O(j))}{O(j)}}{\max\left[\dfrac{(T(1,1)-O(1))}{O(1)},\dfrac{(T(1,2)-O(1))}{O(1)},\ldots,(T(M,K)-O(M))O(M)\right]}$$

$$\mathrm{Fpot}(i,j,l)=\mathrm{Fpf}(i,j)*\mathrm{Fppt}(i,j,l),$$

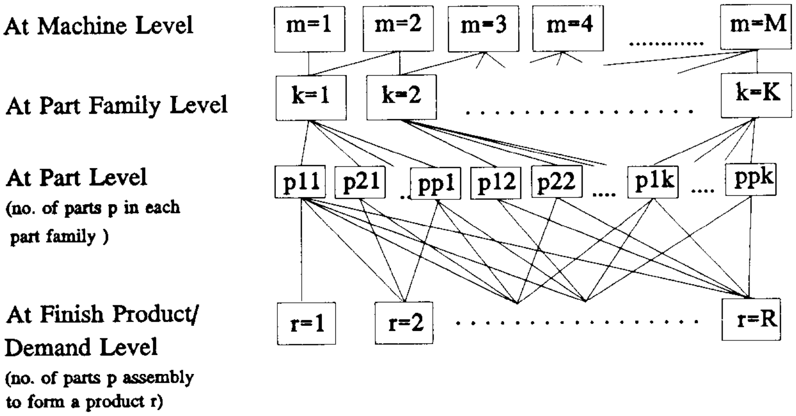

Fig. 5. Manufacturing scenario.

where $T(j, l)$ is the time required to use conventional machine l and $O(j)$ is the maximum time for part j.

(4) Defining the overall and pure component demand flexibility index (Frp(r), Fs(r) Fdt(r) and Fd(r)):

$$\mathrm{Frp}(r) = \frac{\mathrm{OC}(r)/I(r)}{\max\left[\frac{\mathrm{OC}(1)}{I(1)}, \frac{\mathrm{OC}(2)}{I(2)}, \ldots, \frac{\mathrm{OC}(R)}{I(R)}\right]},$$

$$\mathrm{Fs}(r) = \mathrm{Frp}(r) * \mathrm{Fpo}(i, j, l),$$

$$\mathrm{Fdt}(r) = \frac{T(r)/O(r)}{\max\left[\frac{T(1)}{O(1)}, \frac{T(2)}{O(2)}, \ldots, \frac{T(R)}{O(R)}\right]},$$

$$\mathrm{Fdr}(r) = \mathrm{Fppt}(i, j, l) * \mathrm{Fdt},$$

where OC(r) is the operating cost of the part r, $I(r)$ is the inventory cost of finished part r, $T(r)$ is the time required to produce part type r and $O(r)$ is the holding time for part type r. Therefore, demand flexibility for the part is $\mathrm{Fd}(r) = \mathrm{Fppt}(i, j, l)\mathrm{Fdt}(r)$ and the total flexibility index becomes $\mathrm{TF}(r) = \alpha\mathrm{Fd}(r) + (1 - \alpha)\mathrm{Fs}(r)$. For the product, the product is composed of part type r and from that we can easily see

$$\mathrm{TFS} = \frac{(R-1)}{R} \sum_{r=1}^{R} w_r \mathrm{TF}(r),$$

where $r = 1, 2, \ldots, R$.

After defining the flexibility index, it is necessary to use this in the AHP evaluation model. All numeric expressions for each flexibility index can be obtained from [9].

3.2.3. *Quality criteria*

It is measured as a qualitative parameter by the decision-maker in the AHP evaluation model.

3.2.4. *Economic analysis*

For the economic criterion, the net present value method is used. The following assumptions are made:

(1) The salvage value of the equipment equals the book value of each asset at the end of the planning horizon.
(2) With company funds for investment, no additional external funding source is necessary.
(3) Each group depreciation is used for each piece of equipment
(4) Annual increase of unit market price, direct material cost and labor are directly attributed to the annual inflation rate.

Then, the following factors are calculated for the economic analysis:

(a) revenue and
(b) costs – production cost (operating cost, raw material cost, inspection cost, setup cost), maintenance cost, initial investment, depreciation salvage value.

All detailed formulations are explained in [9].

5. Case study

After developing the above methodology, we applied the decision framework to two companies, one in Thailand and the other in Singapore. The first case study is an automotive part manufacturing company in Bangkok, Thailand. For that case study, we developed the questionnaire for phase I and from that we chose the three highly weighted alternatives with weighted scores given in Table 1.

(1) CNC type machines with a conveyor material handling system and worker loading and unloading (Alternative 1).
(2) Machine cell with an AGV material handling system and automatic loading and unloading (Alternative 5).
(3) Machine module with an AGV system, robot loading and unloading system (Alternative 6).

For phase II, we developed three types of layout systems selected from phase I. Goal programming was developed by using the following goals (according to preference) and constraints.

Table 1

Alternative	Weights
1	0.153
2	0.135
3	0.132
4	0.123
5	0.14
6	0.151
7	0.166

Goals

(1) To maximize profit.
(2) To minimize the number of pallets (three times the number of machines in the system).
(3) To fulfil the demand.

Constraints

(1) System constraint – based on space and budget to estimate the maximum number of machines.
(2) Capacity of machine.
(3) Capacity of pallets.

From the goal programming model, we can easily get the number of machines and the possible production rate. We developed the AHP model again to cover the dynamic situation and qualitative criteria based on capacity, flexibility, benefit/cost and quality. For capacity criteria, we intensively used the closed queueing network model written in PASCAL (see [9]) to cover the dynamic situation of the system. For the flexibility index, we used the index already defined in our methodology. For benefit/cost analysis, we used the NPV method over a 10-year time horizon. However, for the last quality criteria, we proposed that a decision preference be used. After defining, calculating and weighing all criteria, the solution for the case study using the CNC machine system with the AGV material handling system is obtained.

6. Conclusions and further study

Before developing new technology in a company, it is necessary to perform the investment analysis carefully. The high investment in machines and material handling systems in an FMS necessitates making careful decisions for selecting types and numbers of machines and material handling systems. Thus, it is necessary to make a detailed analysis on the decision-making model. There are many approaches to this problem. We also developed a two-phase model to cover quantitative and qualitative criteria and the dynamic situation of the system. After developing the decision framework model, it was applied to two case studies. Experience has shown that the methodology proved to be effective in coming up with a well-balanced mix of machines.

There are many interesting ways to extend the model. Firstly, it introduces the idea of developing a phased type model for decision making. Again, as in defining the total flexibility index, it is necessary to modify this index to cover risk analysis and uncertainty of information in the future. Moreover, it is very interesting to link the flexibility index to demand patterns of products. The researcher is now developing a model based on the flexibility index for product design by using concurrent engineering concepts. Finally, defining the quality criterion as a quantitative parameter by using a quality deployment function or developing a new function to catch customer voice is very interesting in decision making.

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