INT. J. PROD. RES., 2003, VOL. 41, NO. 10, 2273–2299

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A design strategy for reconfigurable manufacturing systems (RMSs) using analytical hierarchical process (AHP): a case study

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This paper presents Reconfigurable Manufacturing System (RMS) characteristics through comparison with conventional manufacturing systems in order to address a design strategy towards a RMS. The strategy is considered as a part of a RMS design loop to achieve a reconfigurable strategy over its implementation period. As another part of the design loop, a reconfiguration link between market and manufacturing is presented in order to group products into families (reconfiguring products) and then assign them to the required manufacturing processes over configuration stages. In particular, the Analytical Hierarchical Process (AHP) is employed for structuring the decision making process for the selection of a manufacturing system among feasible alternatives based on the RMS study. Manufacturing responsiveness is considered as the ability of using existing resources to reflect new environmental and technological changes quickly. The AHP model highlights manufacturing responsiveness as a new economic objective along with classical objectives such as low cost and high quality. The forward-backward process is then proposed to direct and control the design strategy under uncertain conditions during its implementation period. The proposed hierarchy is generic in structure and could be applicable to many firms by means of restructuring the criteria. This work is based on a case study in a manufacturing environment. Expert Choice software (Expert Choice 1999) is applied to examine the structure of the proposed model and achieve synthesise/graphical results considering inconsistency ratios. The results are examined by monitoring sensitivity analysis while changing the criteria priorities. Finally, to allocate available resources to the alternative solutions, a (0–1) knapsack formulation algorithm is represented.

1. Introduction

Advanced manufacturing systems need accurately to consider business aspects such as marketing, as well as engineering aspects, otherwise they cannot obtain a reasonable share of a competitive market to justify their investments. Manufacturing systems (MSs) have been developed along with changes of their strategic characteristics such as process technology, market, manufacturing policy, and their adaptability to demand variations, as shown in table 1. Traditional manufacturing systems such as Dedicated Manufacturing Systems (DMSs) were designed for a fixed process technology in stable market conditions through a pushing policy in order only to technically manufacture a single demanded product. In contrast, conventional manufacturing systems, such as Flexible Manufacturing Systems (FMSs) and Cellular Manufacturing Systems (CMSs), are designed for

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Revision received November 2002.

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International Journal of Production Research ISSN 0020–7543 print/ISSN 1366–588X online
http://www.tandf.co.uk/journals
DOI: 10.1080/0020754031000077266

	Manufacturing systems		
Aspect	Traditional Manufacturing Systems (e.g. DMSs)	Conventional Manufacturing Systems (e.g. CMSs, FMSs)	Advanced Manufacturing Systems (e.g. RMSs)
Process technology over time	Fixed	Needs to be adaptable to market	Should be responsive to market
Market	Stable	Predictable	Uncertain
Manufacturing policy	Pushing	Pulling	Customizing
The gap level between MSs and Demand variations [Present/Future]	High/Very high	Medium/High	Low/very low (expected)

Table 1. Changes of strategic characteristics along with evolution of MSs.

limited product types in predictable market conditions with a relatively adaptable process technology through a pulling policy in order to attract more market demands. As time passes, the gap between traditional/conventional MSs and demand fluctuations increases. Next generation manufacturing systems should be responsive to the market for surviving in uncertain market conditions through a customizing policy in order dynamically to adjust system elements to new circumstances.

The need to respond rapidly to changes in market demands creates a need for new designs of Manufacturing Systems (MSs). In order to sustain competitiveness in dynamic markets, manufacturing organizations should provide sufficient flexibility to produce a variety of products on the same system (Chick *et al.* 2000; Hill 1985).

A Reconfigurable Manufacturing System (RMS) is a new paradigm for production systems that addresses the need for introducing greater flexibility into the high production environment in which changes in product volumes and types occur regularly. This can be achieved by reconfiguring the production elements according to changing demands.

2. RMSs' characteristics compared with conventional manufacturing systems

The concept of RMSs has its origin in designing computing systems in which configurable computing systems try to cope with the problem of inefficiency of conventional systems due to their general orientations. The initial idea of reconfigurable computing systems dates from the 1960s (Radunovic 1999). This innovative paradigm dissolved the hard borders between hardware and software and joined the potentials of both. In comparison, the RMSs paradigm is intended to link the potentials of market demands and manufacturing systems that traditionally have been considered as two separate environments.

RMSs have recently been introduced to produce different product families in the shortest time and at the lowest cost without sacrificing quality. The major characteristic of such systems, called *reconfigurability*, is the ability of rearranging and/or changing manufacturing elements aimed at adjusting to new environmental and technological changes. Similarly, manufacturing responsiveness, associated with reconfigurability, is the ability of using existing resources to reflect such changes. The reconfigurability of manufacturing elements is being considered as a new requirement, which plays a key role in future manufacturing systems. Similarly, manufacturing responsiveness has shortly become a new economic objective along with classical objectives such as low cost and high quality. Koren *et al.* (1999) defined a RMS as a manufacturing system designed at the outset for rapid changes in structure as well as in hardware and software components in order quickly to adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements. As can be remarked in the definition, RMSs were assumed to be reconfigurable only within a particular part family. In contrast, Xiaobo *et al.* (2000) considered a RMS as a manufacturing system in which a variety of products required by customers are classified into families, each of which is a set of similar products, and which correspond to one configuration of the RMS.

In this research, a RMS is expected to be able to adjust rapidly to new circumstances by rearranging and/or changing its hardware and software components in order to accommodate not only the production of a variety of products, which are grouped into families, but also a new product introduction within each family. The manufacturing system is then required to be reconfigurable in capacity for volume changes and functionality for family changes. In this way, a reconfiguration link between the market and the manufacturing system is required to reorganize the production system according to varying requirements. The reconfiguration link incorporates the tasks of determining the products in the production range, grouping them into families, and selecting the appropriate family at each configuration stage.

RMSs must be designed with certain characteristics to achieve exact flexibility in response to demand fluctuations. RMSs are described by five key characteristics: modularity, integrability, convertibility, diagnosability, and customization (Mehrabi *et al.* 2000). Modularity in the product design stage as well as in the process design stage enables a RMS to produce different product families with common resources by means of different configurations. As a result, a RMS design must be:

- modular in both product and process design stages,
- rapidly integrated from product to process design,
- rapidly upgradeable in process technology with new operational requirements,
- able to covert to the production of new products within each product family,
- able to adjust capacity quickly whilst changing product volumes (with predictable and/or unpredictable quantities).

Traditional manufacturing systems such as Dedicated Manufacturing Systems (DMSs) are designed to produce only a certain product type with a deterministic demand while using fixed manufacturing elements, such as machines, tools, operators and material handling systems. Conventional manufacturing systems, such as Flexible Manufacturing Systems (FMSs) and Cellular Manufacturing Systems (CMSs), have also not been shown to be full of the above RMSs characteristics. FMSs have focused on multi-purpose manufacturing facilities to make possible the manufacture of a variety of product types. Although FMSs have improved the flexibility of manufacturing systems to respond to changing production requirements, there still exist some limitations in establishing FMSs, and these can be listed as follows.

- The difficulty of design, owing to the large commitment of manpower and skill for the specification and integration of complex manufacturing elements (Borenstein 1998).
- High capital costs and acquisition risks.
- Not economic for higher (or lower) product variety due to the need for investing in higher flexible multi-purpose facilities (or using more flexibility than needed).

On the other hand, CMSs are generally designed according to a fixed set of part families, whose demands are assumed to be stable with long life cycles. When a cell is formed, a single part family with identified demand is assigned to it. A discussion of the limitations of a cellular manufacturing system can be found in Benjaafar (1995) and Flynn and Jacobs (1986). The structural limitations of CMSs can be listed as follows.

- CMSs are designed for predetermined and fixed parts.
- CMSs are not flexible enough to produce new parts.
- CMSs are not economic for demand fluctuations whether in type or volume.
- The cost of redesigning CMSs and layout changes is too high.

As a result, classical CMSs may be known as unconfigurable manufacturing systems. An extension to CMSs by the virtual cellular concept has been reported, based on physically reconfigurable systems using the Group Technology (GT) principles (Rheault *et al.* 1996). Although the virtual cell concept has been proposed in support of classical CMSs, in order to keep pace with the above limitations via reconfiguring cells (Zolfaghari and Liang 1998, Ratchev 1999), the core structural circumstances that come from the nature of cellular configurations are still unavoidable. Some CMSs' shortcomings from the reconfigurability point of view can be listed as follows.

- Uneven and low machine utilisation because of duplication of the same machines in different cells.
- Low flexibility for product variety.
- High changeover cost for cell reconfiguration, e.g. machine relocations.
- Limitation on a new product introduction because of its potential operational dissimilarities with existing products.

The Agile Manufacturing Systems (AMSs) paradigm is another system concept in the manufacturing environment and has the idea of responding quickly in an adaptive manner (Lee 1998). An AMS has been defined as a system that is capable of surviving and prospering in the competitive environment of continuous and unpredictable changes by reacting quickly and effectively to a changing market (Gunasekaran 1998). A literature review (e.g. Jung *et al.* 1996, DeVor *et al.* 1997) shows that a range of agile architectures has been discussed for the development of business environments. However, the design at plant level is still in the earliest stages, which are limited to the identification of the key attributes such as responsiveness, productivity, flexibility and reusability.

RMSs comprise various replaceable modules, with the intention that, once a reconfiguration takes places, a new module replaces an old module (Yigit and Usloy 2002). The modular structure accommodates new and unpredictable changes in the product design and processing needs through easily upgrading hardware and software rather than the replacements of MS elements such as machines.

In the same way, holonic manufacturing systems have been built up from a modular mix of components in order to cope with a rapidly changing environment. To date, the holonic concept has focused on developing an architecture for planning and control functions, which is required for managing existing production systems at the machine level. For example, Chrin and McFarlane (1999) presented a conceptual migration strategy for transferring a traditional manufacture control architecture into a holonic infrastructure. The holonic architecture can be used for reconfiguring the control system of an established RMS into different post-design levels, such as planning, scheduling and execution.

As outlined in figure 1, there are common features between RMSs and conventional manufacturing systems. At the strategic level, the common objectives of the strategic characterization of AMSs and RMSs, such as product variability and rapid responsiveness, are investigated in this research in order to identify a design strategy towards a RMS. At the tactical level, the compatible operational techniques used in FMSs (e.g. machine sharing and flexible layout) and CMSs (e.g. clustering algorithms) can be adapted for the tactical/operational design of RMSs.

In this paper, we focus on the strategic stage of RMS design. This stage needs a basic system concept to describe the system characteristics, and a strategy highlighting the system requirements. Hence, this study begins by considering a conceptual framework for a RMS, which puts an emphasis on RMS distinctive features among conventional systems, such as the reconfiguration link between the market and the

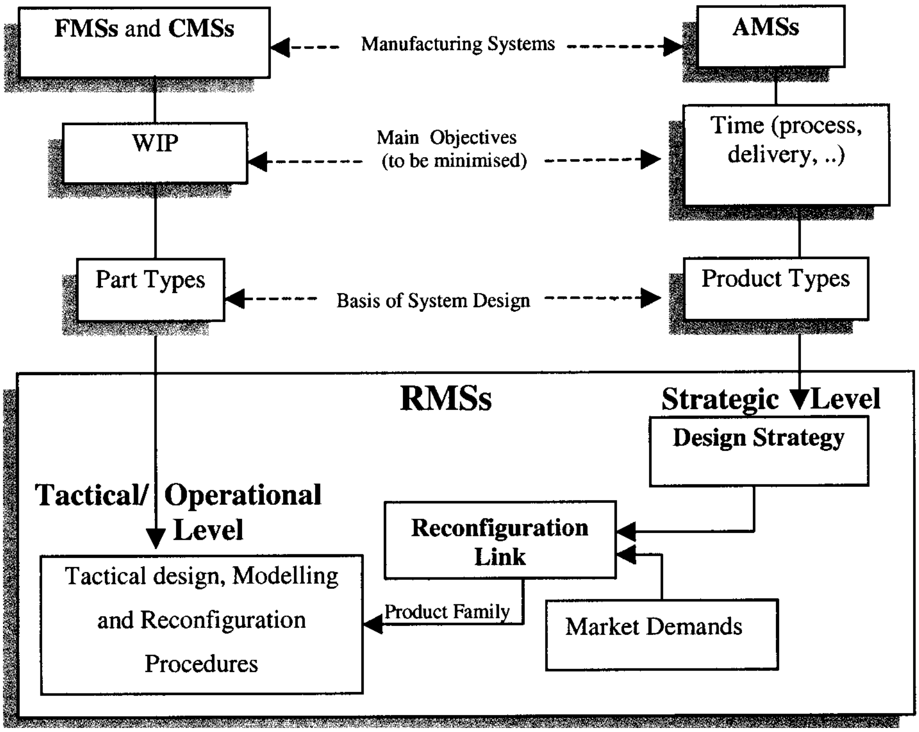

Figure 1. A design perspective of RMSs via developing AMSs, FMSs and CMSs.

manufacturing system. The study is then developed via a design strategy, which aims to highlight the current and future requirements of manufacturing systems. To establish a suitable implementation approach, determining the compatibility of RMSs' requirements with the current and/or next generation of MSs, a model of the Analytic Hierarchy Process (AHP) is proposed through a real manufacturing case study.

3. Reconfiguration link

To fulfil the gap between dynamic market demands and capacity and the functionality of manufacturing systems, a reconfiguration link is necessary to group products into families before manufacturing based on process similarities, as shown in figure 2. Although reconfigurability in the literature is considered only for manufacturing elements, this research aims to develop it to the strategic predesign stage of a manufacturing system. In this respect, products must be reconfigured to each other by means of grouping them into families before manufacturing. The product families will be then selected over the reconfiguration stages in the planning horizon. This results in grouping products into families (reconfiguring products) and then assigning them to the required manufacturing processes over configuration stages. Manufacturing system reconfigurations with the reselection and rearrangement of resources then proceed whilst switching from one product family to another one.

RMSs are not only capable of rapid adaptation to variable quantities and types of products (flexibility in capacity and functionality) for a given part family, they are also open-ended to produce a new product on an existing system (Mehrabi *et al.* 2000). In the proposed reconfiguration link, any new product type should first be assigned to the predetermined and/or new product family in the production range before passing through its manufacturing process with a new system configuration.

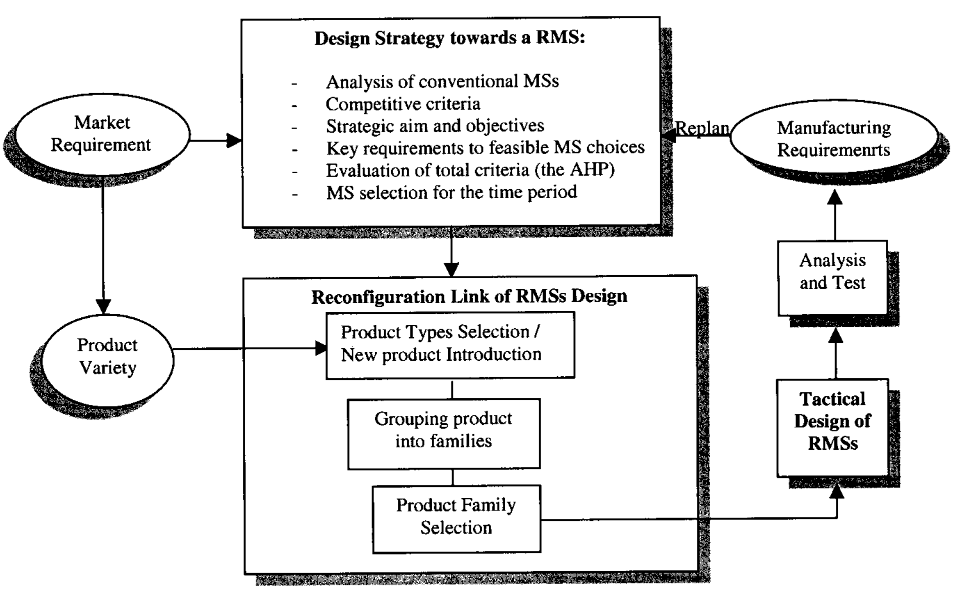

Figure 2. The design loop of a RMS through the reconfiguration link.

The level of utilizing manufacturing facilities at a current configuration for the next configuration is another design issue to be evaluated. This economic value, called 'reusability', can reflect the economic adaptability of an existing RMS whilst switching to a new product type. The task of a reconfiguration link in RMSs is to maximize reusability so as to arrange and assign product families in the most appropriate order according to the available facilities over configuration stages. We are developing the application of the reconfiguration link concept via grouping and selecting products in the design key of RMSs in our further research.

4. A design strategy for RMSs through the use of the AHP model

The pre-design stage of a RMS is to clarify how well its design objectives can meet the current and future requirements of the manufacturing system in long, medium, and short term planning. To demonstrate effectively the requirements of a RMS as a future system for a manufacturer and to evaluate the related objectives, its design strategy must first be assessed. Making a decision on the requirement of (re)designing a manufacturing system towards a RMS enables managers and designers confidentially to support and perform the next phase of the tactical/detailed design when it is needed.

The objective of this section is to implement the RMS concept, highlighting its key characteristics among conventional systems through a decision making process in order to justify the investment on its tactical design. The first step is to construct a model to evaluate the manufacturing system requirements and the system alternatives as criteria. Due to the complexity of the decision process involving interacting elements, a multi-criteria decision-making approach is required to support managers in selecting an optimal strategy en route to the appropriate manufacturing choice.

To date, very little work dealing with the strategy and design of RMSs has been published. To structure a design strategy for a RMS, a decision making approach can be applied to evaluate the objectives, criteria and feasible alternatives as the manufacturing choices to be designed. However, multi-criteria analytical-decision tools to aid in strategic decision making are relatively rare. This paper is an attempt to identify the strategy justifying the design and utilization of a manufacturing choice based on the RMS study by means of the Analytical Hierarchical Process (AHP).

4.1. *Introduction to the AHP*

The Analytical Hierarchical Process (AHP) developed by Thomas Saaty (1980), is one of the multi-criteria decision making approaches that decomposes a complex problem into a hierarchical order. Pairwise weighing among n elements in each level leads to an approximation to $a_{ij} = w_i/w_j$ which is the ratio of the weight of element i to element j. The estimated weight vector w is found by solving the following eigen-vector problem:

$$\mathbf{A}w = \lambda_{\max} w, \tag{1}$$

where the matrix $\mathbf{A}$ consists of a_{ij}s, and $\lambda_{\max}$ is the principal eigenvalue of $\mathbf{A}$. If there is no inconsistency between any pairs of elements then a_{ij} is equal to $1/a_{ji}$ for any i and j, and we have:

$$\mathbf{A}w = nw. \tag{2}$$

In reality, consistency does not usually take place and the formulation (2) can be expressed as $\mathbf{A}w = \lambda_{\max} w = E$, where E is the principal eigenvalue, a value around n (the total number of elements in the same level), and E is the eigenvalue. To estimate E, each column of $\mathbf{A}$ is first normalized and then averaged over its rows. Eigenvector E is used to find the relative importance of each element with respect to the higher level of hierarchy. The Inconsistency Ratio (IR) is given by $(\lambda_{\max} - n)/(n-1)$, which is the variance of the error incurred in estimating matrix $\mathbf{A}$. If an inconsistency becomes more than 10%, the problem and judgements must be investigated and revised (Saaty 1994).

4.2. *Related literature covering strategic/tactical decision-making using the AHP*

Not many researchers have used AHP for strategic/tactical decision-making in production systems. At the strategic level, the AHP approach was applied for selecting next-generation manufacturing paradigms based on four objectives: the environment, product, technology, and social for future implementation (Alvi and Labib 2001). As discussed in Oeltjenbruns *et al.* (1995), the strategic planning in MSs has fundamental steps when using the AHP approach, as follows: (i) specification of investment alternatives and evaluation criteria, (ii) pairwise comparisons of criteria and categories, (iii) rating of investment alternatives for each category, and (iv) overall ranking of investment alternatives for making decisions. The selection of advanced technology using the AHP can be merged with quantitative variables through cost/benefit and statistical analysis (Kengpol and O'Brien 2001). As many factors contribute to the successful decision of whether to implement an advanced technology, the problem is a multi-criteria decision process with different priority levels, and unquantifiable attributes (Yusuff *et al.* 2001).

For a continuous improvement process in industry, Labib and Shah (2001) defined the required decision elements of their AHP model in order to obtain a strategy as follows: (i) scenarios: four possible combinations of two levels of demand and supply, (ii) decision-makers, (iii) objectives, and (iv) options (strategies).

At the tactical level, the AHP can be applied to select a plant layout configuration, such as group technology, transfer lines, and functional layout, in respect to the defined objectives and their preferences. Abdul-Hamid *et al.* (1999) applied an AHP model for the selection of best layout based on three main objectives: flexibility, volume and cost, using a knowledge-based system in order to solve a given structure. Nevertheless, the user-friendly AHP software 'Expert Choice' applied in this research is more applicable and accessible to engineers and managers. This software is able to facilitate the decision process through monitoring the sensitivity analysis of various criteria with dynamic synthesis/graphical results.

5. The AHP model

In this research, the Analytical Hierarchical Process (AHP) is employed as a multi-criteria strategic justification approach for a manufacturing choice based on a RMS study. The proposed AHP model breaks down the complex structure of the decision process to a hierarchical sequence in order to determine the relative importance of each manufacturing alternative through pairwise comparisons. In the model, the common design parameters for conventional MSs, such as cost and quality, plus new requirements such as responsiveness, are taken into account. By trading off among all relevant objectives, criteria, and manufacturing system alternatives, a (re)design strategy towards a RMS is achieved.

This AHP model is intended to support management's strategies on planning and (re)designing manufacturing systems over their planning horizons. In this way, the optional design strategy can be defined as 'a plan for the manufacturing system to meet long term manufacturing objectives, possibly leading to a RMS design as an alternative solution'. In particular, the AHP model is examined by using Expert Choice software during an industrial case study to assist the managers in selecting the most appropriate manufacturing system from a set of feasible alternatives. The results of the strategy will be used to redesign the existing system towards the desired system when needed. The AHP model consists of the following steps:

Step 1. Set the strategic objectives and criteria for the evaluation of the manufacturing system under study.
Step 2. Structure the decision hierarchy leading to MS choices that are the most feasible and best suited to the nature of the manufacturing system organization.
Step 3. Determine the weight or importance of each attribute with the support of the company's upper level management through questionnaires.
Step 4. Evaluate and perform the rating of each criterion, subscription, and alternative with respect to the next higher objectives or criteria.
Step 5. Identify the higher rating preferred alternative and analyse the solution with respect to the changes of importance in criteria.
Step 6. Determine the strategy for the selection of most fitted manufacturing systems to be designed and established over planning horizons.

In this section, we propose an AHP model in order to systematize an early design strategy towards a RMS, which refers to the preferred technology over planning horizons as the main goal (hierarchy level 0). The strategic parameters for this model can be hierarchically categorized into five levels as follows.

Level 1. Planning horizons.
Level 2. Decision makers (actors).
Level 3. Objectives of actors.
Level 4. Criteria that satisfy those objectives.
Level 5. Alternatives/decisions.

The proposed model is generic and is intended to consist of managerial parameters that are strategically valuable to many companies. In this respect, the hierarchy has general levels, i.e. goals, objectives, and sub-objectives as criteria that can be considered generic. However, other levels of the hierarchy, which include planning horizons, actors and alternatives, must be adapted according to the specific nature of the company under study. For example, feasible alternatives (manufacturing choices) may differ from one company to another because of influencing factors such as the available technology, budget, and the volume and type of products to be manufactured.

5.1. *Impact of planning horizon (level 1)*

One of the most important factors that influences the selection of a MS is the period of the planning horizon. The planning horizon can be broken down into a number of time periods in order to reduce the uncertainty and risk caused over a long variable period. The first level of the AHP model deals with three major planning periods in the strategic framework, with the separate planning criteria as follows.

(i) Short Term (ST): to redesign a MS to respond quickly to current demand variations (under two years).
(ii) Medium Term (MT): to (re)design a MS to demand changes, while introducing a new product within a specified product family is possible (between 2 and 5 years).
(iii) Long Term (LT): to design a MS to reflect any changes in products, while introducing a new product family is possible (over 5 years).

To synthesize the weights of the criteria for each time period, planning horizons themselves must be prioritized. The planning horizons' priorities can be elicited through investigating the manufacturing strategy of the plant, by way of negotiation with all expert people influencing the decision process, such as managers, engineers, and system designers.

5.2. *Decision-makers (level 2)*

The AHP model emphasizes the idea of team decision making by using input data from different groups within a company. This AHP model considers three actors for redesigning an existing MS toward a RMS. An actor is an individual or a group, which plays a significant role in responding to forces that shape current events, and therefore future outcomes (Labib *et al.* 1996). Accordingly, the recommendedactors influencing the decision making in the proposed model are as follows:

Plant Manager(s) (PM)—Top manager(s) of the company who can evaluate the hierarchy of different criteria and provide judgement on the desirability of alternatives with respect to qualitative and intangible criteria.

Shop floor Manager(s) (SM)—Top manager(s) of the production system who can provide technological based performance data including feasibility and economical aspects of alternative manufacturing choices.

Manufacturing Designer(s) (MD)—Top manager(s) of the manufacturing design group who can support the decision process through evaluating and analysing an entire hierarchy, including the impact of planning horizons, actors, objectives, and sub-objectives on alternatives. The MD can also provide technical information to evaluate the feasibility of a RMS choice and perform decision analysis, economic and risk analysis to valid the final decision.

It is important to note that each of the actors above, can be either a single manger and/or a group of experienced people working in the relevant departments of the plant.

5.3. *Objectives and criteria (levels 3 and 4)*

The strategic objectives towards designing RMSs are identified as Responsiveness (R), Cost (C), Quality (Q), Inventory (I) and operators' skill (S). In order to facilitate an accurate decision analysis, all strategic objectives are broken into relevant criteria as follows.

5.3.1. *Responsiveness (R)*

Manufacturing responsiveness is related to the ability of a manufacturing system to utilize its existing resources to make a rapid and balanced response to predictable and unpredictable changes (Gindy and Saad 1998). Obviously, different types of MSs have different levels of responsiveness. The proposed model gives great attention to this objective as a new manufacturing system requirement. This objective is then compared with other strategic objectives, such as product quality and cost. Reusability as an economic/strategic factor significantly contributes to the rapid responsiveness (R). Four sub-objectives (criteria) under the umbrella of responsiveness are considered in the hierarchy to evaluate the importance of responsiveness (R) over the MS alternatives. These are:

- a wide variety of products (w1): which represents the ability of the plant to manufacture a range of products with different processing requirements,
- new product introduction (n): which represents the ability of the plant to accept a new design of products,
- rapid response to changes of product families using existing facilities (d): which represents the ability of the plant to change its capacity and functionality with maximum reusability against demand fluctuations,
- reduction of lead-time for product development (t): which represents the ability of the plant to change tools for a given mix of products within a family with low ramp-up and set-up times. This criterion will be more important when batch sizes of product types within a family are very small, and therefore the set-up time of retooling machines must be short.

5.3.2. *Product cost (C)*

Product cost can be decomposed into criteria as follows:

- Raw material (r1): which include all direct material used in manufacturing products.
- Process (p1): which includes:
  - the cost of capital investment on manufacturing equipment such as machines, tools, and material handling. Reusability can reduce extra investment for system reconfiguration,
  - the operating cost consists of machine utilization, operators running machines, and workers on the shop floor responsible for other tasks such as maintenance, transportation, quality control, and cleaning,
  - the indirect cost (i), which consists of energy, engineers, and personnel officers in production planning, accounting, so on.

5.3.3. *Product quality (Q)*

This comprises:

- raw material (r2), which is concerned with the input quality of purchased material,
- process (p1), which is concerned with the quality of parts in the manufacturing routes,
- finished products (g), which is concerned with total quality of ordered products for delivery.

5.3.4. *Inventory (I)*

This comprises:

- raw material (r3) which is the inventory in the warehouse of the parts to send to the system,
- Work In Progress (WIP), (w2) which is the inventory of parts in process before the manufacturing process is completed,
- final product (f1), which is the inventory of the products before delivering to customers.

5.3.5. *Operator skills (S)*

This comprises:

- motivation (m), which encourages operators to activate extra effort for reconfiguring the system,
- training (tr), which facilitates the learning process for the changes of tasks when reconfigurations take place,
- facilities type (f2), which affects the required skill, e.g. using dedicated and flexible machines requires different levels of expertise.

5.4. *Alternatives (level 5)*

The final level of the hierarchy involves the specific manufacturing choices of a company for its strategic plan. The alternatives may differ from one company to another depending on the existing system and feasible alternatives. These may be traditional/conventional systems such DMS, CMS, FMS, and/or an advanced system such as RMS. In the generic model, they are assumed to be the Existing Manufacturing System (EMS), Reconfigurable Manufacturing System (RMS), and the Hybrid Manufacturing System (HMS), which can be characterized by a means of a combination of EMS and RMS according to the type of company.

5.5. *Structure of the model*

Modelling the decision elements together in a logical structure of a hierarchy can result a structured framework as presented in table 2 and figure 3.

The proposed AHP is generic in structure and assists plant managers in structuring multi-actors, multi-periods, and multi-criteria strategic decision making for the potential design and implementation of a RMS. Once the hierarchy is structured, the quantitative evaluation through pairwise comparisons can be performed for all elements at each level with respect to the next higher-level elements. The assessment process starts with pairwise comparisons between planning horizons by managers in order to prioritize the impact of each period on the design strategy, e.g. offering priorities: 0.687, 0.186 and 0.127 for LT, MT and ST respectively. Similarly, pairwise comparisons between actors (PM, SM, MD) with respect to each planning horizon result in a likelihood matrix. As shown in table 3, the expected weight of each actor is multiplied by the weight of each planning horizon (as presented in parentheses), and then summed over the corresponding row to obtain the global importance of the actor, as presented in the last column.

The next process is to compare objectives and criteria by actors. For example, pairwise comparisons between objectives and criteria by plant manager with respect to LT, result in the objectives' priorities as illustrated in table 4. The E's values are given in the last column and IR is equal to 0.06.

Goal: (Re)Design of a MS for reconfigurability—Level 0				
Level 1: Planning horizons	Level 2: Decision makers (actors)	Level 3: Objectives	Level 4: Criteria	Level 5: Alternatives
Long Term (LT)	Plant Manager (PM)	Responsiveness (R)	• The ability to produce a wide variety of product type (w1) • To let a new product be produced (n) • To quickly respond to changing demand (d) • Reduction of the lead time of product development (new improved models) (t)	EMS: Existing Manufacturing System (product lines)
Medium Term (MT)	Shop floor Manager (SM)	Product cost (C)	• Raw material cost (r1) • Process cost (machines, energy, operators) (p1) • Indirect cost (production planning, inventory maintenance) (i)	RMS: Reconfigurable Manufacturing System
Short Term (ST)	Manufacturing Designer (MD)	Product quality (Q)	• Quality of raw material (r2) • Process quality (p2) • Finished goods	HMS: Hybrid Manufacturing Systems (EMS + RMS)
		Inventory (I)	• Raw inventory (r3) • WIP inventory (w2) • Final product inventory (f1)	
		Operators skills (O)	• Motivation (m) • Training (tr) • Facilities (dedicated or multi-purpose ones) (f2)	

Table 2. Strategic design parameters in the AHP model.

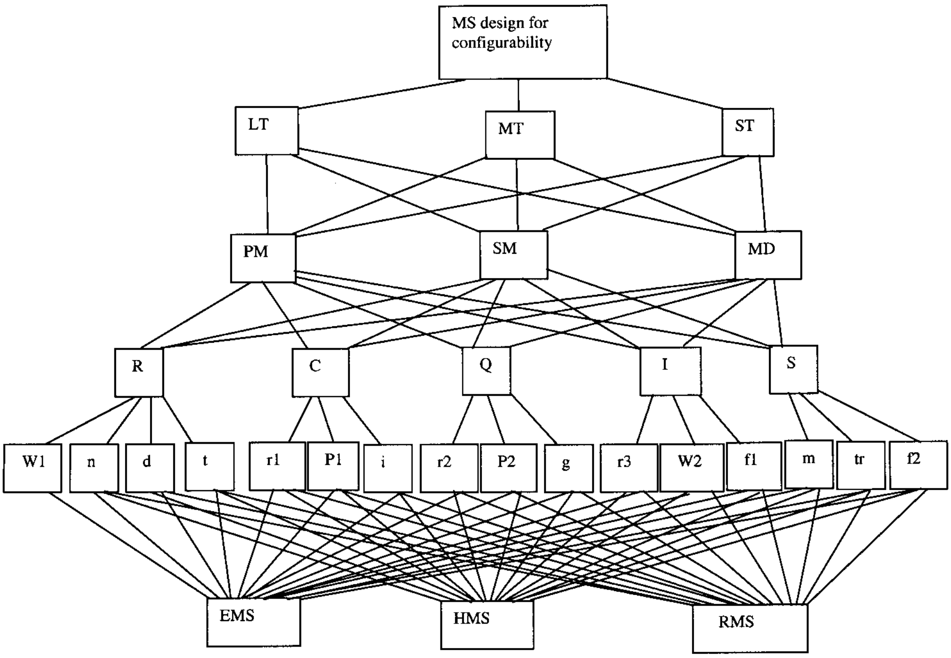

Figure 3. The AHP structure of the proposed model.

Goal	LT (0.687)	MT (0.168)	ST (0.127)	Global importance of actors
PM	0.540 (0.371)	0.117 (0.019)	0.678 (0.086)	0.476
SM	0.163 (112)	0.268 (0.045)	0.101 (0.013)	0.175
MD	0.297 (204)	0.614 (0.103)	0.226 (0.029)	0.336

Table 3. A likelihood matrix of decision makers.

Strength of objectives—Plant Manager (PM)						
MS design	R	C	Q	I	S	E
R	1	1	3	3	3	0.137
C	1	1	1	4	3	0.184
Q	$\frac{1}{3}$	$\frac{1}{3}$	1	4	1	0.279
I	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{4}$	1	3	0.064
S	$\frac{1}{3}$	$\frac{1}{3}$	1	$\frac{1}{3}$	1	0.336

Inconsistency rate = 0.06

Table 4. A comparison matrix of objectives by PM with respect to LT.

6. Validation of the AHP model through a case study

A manufacturing company (Arvin Meritor in Birmingham) agreed to be a case study to facilitate investigation and verification of the AHP model in practice. The company is a branch of Meritor (formerly Rockwell Automotive), and is a global supplier of components and systems for light, commercial and special vehicles. The company produces a large variety of spare parts for automotive industries. The existing layout of the manufacturing system is based on production lines, each of which is dedicated to an individual existing customer. The major problem that the company suffers from is the lack of flexibility at each production line to cope with product design changes. In this respect, there has recently been a trend to standardize similar products of different customers at the design stage in order to maintain the existing system, without the need to increase the functionality of each product line.

The applicability and feasibility of the proposed AHP model is successfully demonstrated at Arvin Meritor. The systematic approach of the model assists managers in understanding better the process that they require for their future investment plan when there is a need to design a new manufacturing system.

As the model is very sensitive to the preference values between AHP parameters, the input data must be carefully obtained from experts' opinions. Input from experienced engineers for group decision-making can enrich the model with accurate data. This can result in the motivation of managers to support the tactical/detailed design as the next phase. The sensitivity analysis shows that HMS always outperforms the other manufacturing alternatives at the company, but it must be mentioned that the result depends on the input data and assumptions.

The proposed AHP has provided a realistic method to evaluate quantitative and qualitative aspects for the selection of a manufacturing choice, based on a RMS study, through a real industrial case study. The model enables the plant management systematically to structure their strategic decision making problem, and simultaneously to evaluate the feasible alternatives through a set of individually chosen and weighted criteria. Analysis features in Expert Choice through sensitivity graphs have enhanced the model to interpret the results over a range of ranking priorities of criteria.

The company is committed to achieving a planned technological development over two horizon periods: short and long term. Accordingly, in the generic AHP model, the medium planning period (MT) is eliminated for the adaptation to this specific condition.

The AHP model is constructed using Expert Choice software as demonstrated in figure 4. As discussed in Son *et al.* (2000) the economic benefit of RMSs are comparable with DMSs and FMSs. The alternative manufacturing systems are presented at the bottom of the screen in terms of leaf nodes as follows.

Dedicated Manufacturing System (DMS)

Existing manufacturing is based on product lines in a produce-to-order environment. Each production line is dedicated to a predetermined product with an operational sequence to complete limited versions of the same model. The high demand and a few product types justify the investment in the DMS, and provide a low manufacturing cost for the company. Although, each product line can exactly achieve the manufacturing requirements of its fixed demands, its capacity is significantly limited and inflexible. In other words, each line has already been

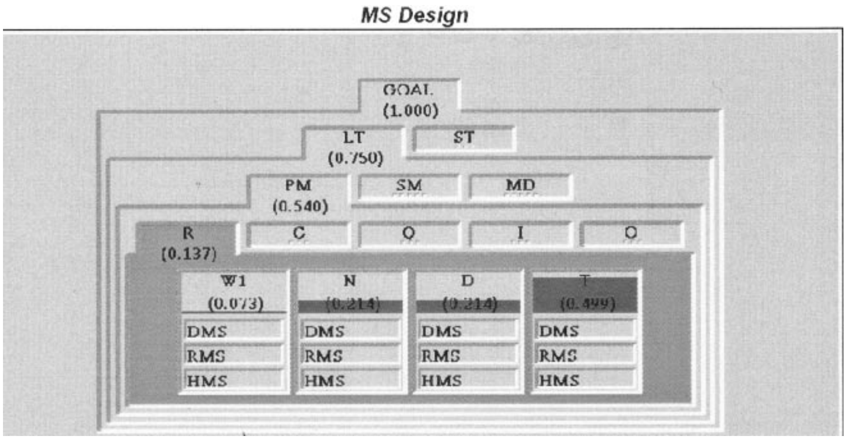

Figure 4. The structure of the AHP model built in Expert Choice for the case study.

designed based on the maximum demand of an identified product without considering demand fluctuations.

The major current problem of this active system is the dependency on car models supplied by Arvin Meritor. This creates a need for process reconfiguration in the product lines while developing models from suppliers. Introducing a new product into the existing system (parameter n) creates a need to reconfigure MS. Once a new car model with new designs of spare parts is introduced, an extra production line with individual facilities such as dedicated machines, operators and control systems should be designed and installed. Obviously, this will impose the high cost of new investment to the company, even if the method is feasible. Recently, there has been a trend in the company to develop product design towards a modular/standard base in order to standardize products regardless of their customers. This will facilitate the reconfiguration of existing production lines to achieve variant modular product lines with different configurations based on module instances of products in the production range. As a result, managers can reach more reconfigurable production lines without capital investment on higher flexibility.

Reconfigurable Manufacturing System (RMS)

As mentioned before, there is a trend in the company to design products in a standard/modular base in order to facilitate their production using existing facilities. In short term planning, this RMS feature will support DMS in terms of avoiding investment on extra lines by easily reconfiguration of the products within the corresponding family. In this way, different module instances from variants of modular products will be assigned to suitable configurations of the corresponding production line. Furthermore, increasing product variety and uncertainty in market demands in volume and type will also impose the application of a standard/modular concept in redesigning of the whole manufacturing system. As a result, in long term planning, the manufacturing system will need to be replaced with a RMS when the managerial response to increasing demand uncertainty and greater product families becomes more important.

Assuming an FMS alternative is considered instead of a RMS choice for the future of the company, and the multipurpose manufacturing facilities designed for a specific range of products in a FMS need to be frequently fine-tuned with regard to capacity and functionality and/or replaced with higher flexible ones. This is not always feasible due to the limitation of FMS functionality and/or economics, as it may impose an extra capital investment on more flexibility and/or a higher operating cost on the system. Considering the following issues in the manufacturing environment, a RMS is expected to be the most suitable future alternative:

(i) the existing trends towards modularity on product and process design,
(ii) high variety (but similar) product types, and
(iii) the adaptable nature of the plant to RMS characteristics, such as the feasibility of a combination of existing similar product lines to reach a single RMS with different configurations based on module instances (reconfigurable layout).

A modular reconfigurable system integrated from first to last in product design, reconfiguration link, and a modular manufacturing process with movable facilities, can deal with the future uncertain conditions. The cost of reconfiguration in a RMS for a new product family must be less than the cost of installing a new product line in DMS with dedicated facilities and/or capital investment for a higher flexibility in HMS. Otherwise, a suitable strategy may push the manufacturing system back so as to install a complete product line for the new product family instead of reconfiguring the future active RMS. In addition, at the tactical design stage, as discussed in Lee (1997), machine relocations for the RMS are only suggested when the material handling cost for a new configuration is greater than the system relocation.

The RMS alternative is expected to be capable of:

- producing a wider variety of products than the existing range (w1),
- new product introduction within each family (n),
- adaptability to unpredictable demands (d) using existing facilities (reusability)
- common facilities utilization for modular products (f2),
- cost effective manufacturing for a wide range of products (C) by increasing reusability.

Hybrid Manufacturing System (HMS)

Suddenly springing from the existing system to a RMS configuration may not be feasible and economic, particularly in the short or medium term. In addition, market conditions may enforce the system keeping certain product lines still working. To enable the MS to support and keep pace with the current market requirements, a mix of two extreme process choices of DMS and FMS, so-called HMS, is proposed as another alternative for the medium-long term planning. As a part of HMS, some specified product lines with deterministic/reliable demands can efficiently continue former productions for medium term planning; on the contrary, as another part of HMS, for the other existing/future products, a FMS is necessary to be designed and established.

To simplify the description of the judgement logic of the AHP, the above alternatives can be ranked with respect to each of the criteria, planning horizons and actors. Table 5 demonstrates the importance of alternatives with respect to PM in three main levels of low, medium and high priority.

		Alternative					
		Planning horizon LT			Planning horizon ST		
Objective	Criterion	EMS	HMS	RMS	EMS	HMS	RMS
R	w1	Low	High	Medium	Low	High	Medium
	n	Low	High	High	Low	High	Medium
	d	Low	High	Medium	High	Medium	Medium
	t	Low	High	High	Low	High	High
C	r1	Low	High	Medium	Low	Medium	Medium
	p1	Medium	Medium	Medium	Low	Medium	Medium
	i	Medium	Medium	High	Low	Medium	Medium
Q	r2	Medium	Medium	Medium	Medium	Medium	Medium
	p2	Medium	Medium	Low	Medium	Medium	Medium
	g	Low	High	Medium	High	High	High
I	w2	Medium	Medium	Medium	Low	Medium	Medium
	w2	Medium	Medium	Medium	Low	Medium	Medium
	f1	Medium	High	High	Low	Medium	Medium
O	m	Medium	Medium	Medium	Low	Medium	Medium
	tr	Medium	Medium	Medium	Low	High	High
	f2	Medium	Medium	Medium	Low	Medium	High

Table 5. The importance of alternatives with respect to criteria ranked by PM.

6.1. *Results*

Sets of questionnaires have been prepared for data gathering in order to prioritize objectives, criteria, and alternatives by actors aimed at strategic design for the plant. To clarify the process of data gathering, a sample of the questionnaires used in the company and created by Expert Choice is presented in figure 5.

The synthesis judgement of alternatives suggests an alternative solution as sorted to HMS > RMS > DMS having the priorities 0.372, 0.353 and 0.275 respectively, with inconsistency ratio 0.06. This means that HMS is the most preferred system, furthermore RMS is preferred to DMS. This model enables the decision process to derive a synthetic judgement from each actor's point of view, which highlights the actor's priorities over the alternatives. For instance, a synthesis of judgement with respect to PM and LT indicates that HMS is remains the preferred alternative.

6.2. *Analysis and discussion*

To get a precise analysis of the criteria, the manufacturing choices would simultaneously be implemented in the plant, but this may never happen. The purpose of this section is not to calculate the exact analysis of different manufacturing choices, but rather to find the general benefits of their trends whilst changing criteria. Some important issues related to the results prepared by Expert Choice in each planning horizon are discussed as follows.

6.2.1. *Long term planning*

As shown in figure 6, HMS is always the best alternative for the long term planning (IR = 0.07). The linear ascending function of HMS clarifies that changing the priority of LT does not affect its preference versus RMS and/or DMS. In other

MS Design

Node: 21000

Compare the relative PREFERENCE with respect to: PM < ST < GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	R	9	8	7	6	5	4	3	2	1	2	3	4	(5)	6	7	8	9	C
2	R	9	8	7	6	5	4	3	2	1	2	3	4	(5)	6	7	8	9	Q
3	R	9	8	7	6	5	4	3	2	1	2	3	4	(5)	6	7	8	9	I
4	R	9	8	7	6	5	4	3	2	1	2	(3)	4	5	6	7	8	9	O
5	C	9	8	7	6	5	4	3	2	1	2	(3)	4	5	6	7	8	9	Q
6	C	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	I
7	C	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	O
8	Q	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	I
9	Q	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	O
10	I	9	8	7	6	5	4	3	2	1	2	(3)	4	5	6	7	8	9	O

Abbreviation	Definition
Goal	MS Design
ST	Short Term
PM	Plant Manager
R	Responsiveness
C	Cost
Q	Quality
I	Inventory
O	Operator Skill

Figure 5. A sample of the questionnaire produced by Expert Choice.

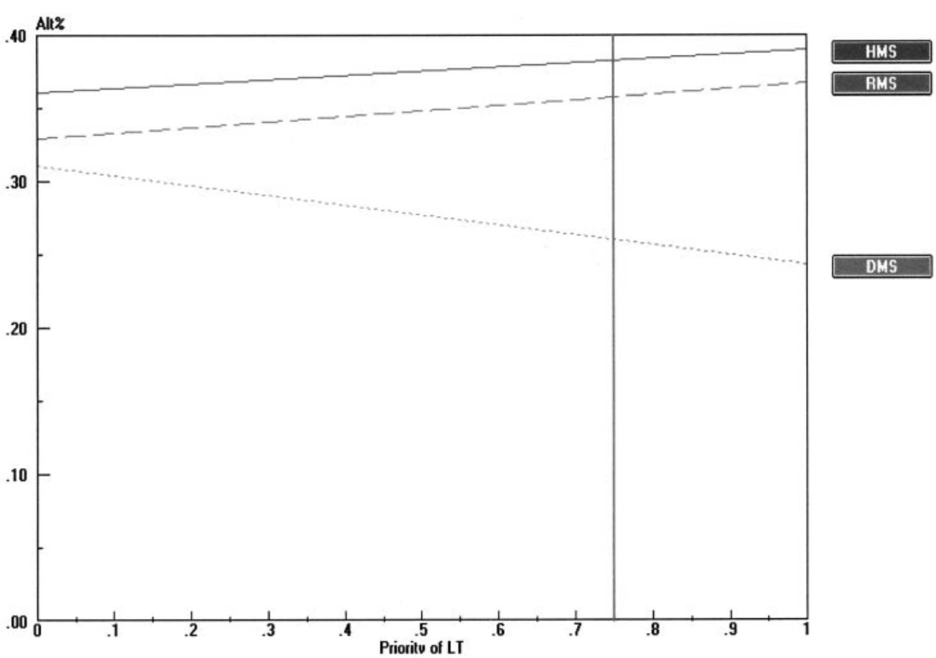

Figure 6. Gradient sensitivity with respect to LT.

words, in long term planning, actors realize that the company needs to keep up some production lines as in the past, but, for a few existing/new products, the establishment of RMS is recommended.

Actors may have created different solutions with different priorities. In the long term, the AHP model offers solutions: HMS > RMS > DMS, RMS > HMS > DMS and HMS > RMS > DMS with respect to PM, SM and MD when IRs are 0.08, 0.06, 0.09 respectively. Although changes in the importance degree of each actor and/or criteria result in changes of the alternative priorities, an increase in the responsiveness degree and the importance of actor PM have not changed the overall solution of HMS > RMS > DMS.

6.2.2. *Short term planning*

In short term planning, the overall solution is still HMS > RMS > DMS (IR = 0.08). However, both actors SM and MD have another solution of RMS > HMS > DMS. By either decreasing the importance of actor PM (below 0.45) or slightly increasing the importance of SM and/or MD the solution will change to RMS > HMS > DMS. On the other hand, the actor MD has been shown to be sensitive to the solutions with respect to R. As shown in figure 7, shifting the vertical line representing the priority of R left or right, will change the solutions to DMS > HMS > RMS and RMS > HMS > DMS respectively. This means that from MD's point of view, DMS can continue if the importance weight of R is not significant among other objectives (below 0.25). Conversely, with a great importance weight of R (over 0.75), MD recommends changing the solutions to RMS > HMS > DMS. As a result, the responsiveness degree (R) significantly affects the given solutions in the short term planning.

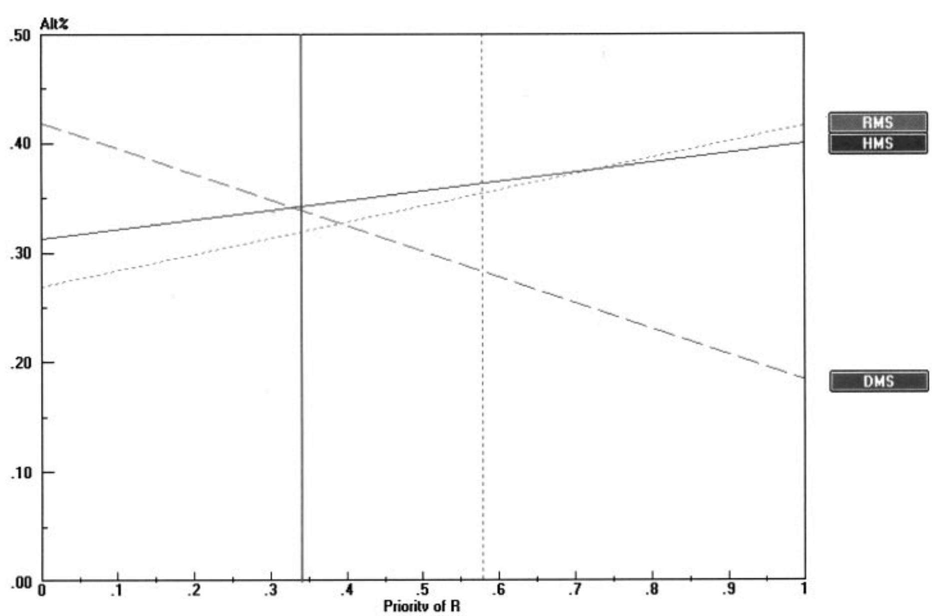

Figure 7. Gradient sensitivity with respect to R.

6.3. *Recommendations*

Strategic-adaptive planning is necessary for the future of the company, as a process of learning, managing, and upgrading system behaviour. Therefore, we need to re-plan and control the design strategy rather than simply reacting. As responsiveness is considered to be the major objective for the establishment of a future manufacturing system at the company, MS choices need to be assessed with respect to R whilst changing its priority. The manufacturing alternatives may have increasing, decreasing, and or indifferent trend while increasing the importance of R among other objectives. The analysis of the AHP model reveals that HMS, the overall preferred manufacturing system, has an increasing trend over R. It means that an increase in the R level improves the rank of HMS as the appropriate solution for rapid responsiveness.

As shown in figure 8, the following results for the strategy of the company can be achieved.

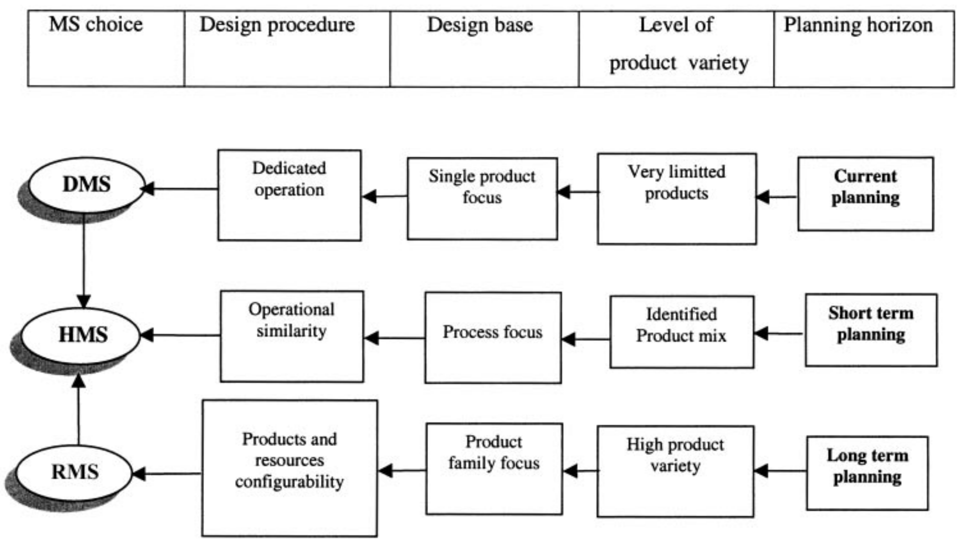

Figure 8. A proposed approach to redesign the Arvin Meritor MS.

Strategic design configuration	Investment (£k)	Expert operators	The time of system (re)design and establishment (weeks)	Extra equipment (units)	Strategic risk level (%)
EMS	200	5	10	15	5
HMS	300	15	20	25	10
RMS	400	30	35	40	25
Available Resonances/upper allowance limit	400	20	35	40	20

Table 6. Matrix of required and available resources for the strategic plan.

For the current planning, the system is characterized as having very limited products: a single product focus with dedicated operations. Therefore, DMS can solve the existing requirements of the company. In contrast, for the short term planning, in which the system is expected to have an identified product mix and process focus based on operational similarity, a need to redesign the system is explored. Accordingly, for the limited but wider range of products, HMS is recommended to be substituted with the existing layout. For the long term planning, the system is potentially characterized by a high product variety, and a product family focus in which products and manufacturing resources must be reconfigured for any product changes. It then appears that a RMS design is required.

7. Risk and uncertainty

In the AHP model, planning horizons (LT, MT, ST) are considered to reduce the impact of uncertainty and risk over time by assigning each criterion to a specific time period. In other words, we have an individual hierarchy that is to be assessed for each planning horizon, leading to an individual design strategy. Each criterion must have its three priorities with respect to LT, MT, ST. In addition, as future factors may influence the selected strategy, the criteria must be revised for each time period and vice versa. In this respect, the pairwise comparisons would be dealt with a revision cycle that indicates:

- which manufacturing system choice is more likely to be designed during the time period and how effectively?
- during which time period a manufacturing system alternative is most likely and how strongly?

Accordingly, in the implementation process of the strategy, a dynamic process (reconfigurable strategy) for evaluating the AHP model is essential. We propose a periodic strategic revision from two to four years for the company: two years to give sufficient time for the effects of the strategy, and four years to prevent the manufacturing system from resistance against changes. In contrast, all the AHP attributes can be regularly revised and interpreted, e.g. on a six-monthly basis as a means of tactical revision.

The strategic/tactical revisions can be developed through a forward–backward process. The forward–backward process interacts hierarchies in order to direct and control the likely future towards the desired future (Saaty and Kearns 1991). The forward process provides a hierarchy for the assessment of the state of the likely MS choice. In turn, the backward planning process provides the hierarchy for controlling and steering the forward process towards the desired strategy by using a composite scenario that is a combination of the MS alternatives in the forward hierarchy.

As depicted in figure 9, the backward process consists of six levels: (1) desired MS, (2) MS choices, (3) state variables, (4) actors, and (5) policies. The composite scenario is represented by state variables, i.e. profit, changeover time, changeover cost, machine utilization, quality, customer satisfaction, and risk. During the implementation period of MS, the state variables themselves must be prioritized first and then with respect to each MS alternative in order to achieve a composite measurement. The composite value of this reconfigurable AHP will be used as a degree of convergence between the likely and desired strategy identified in the backward process.

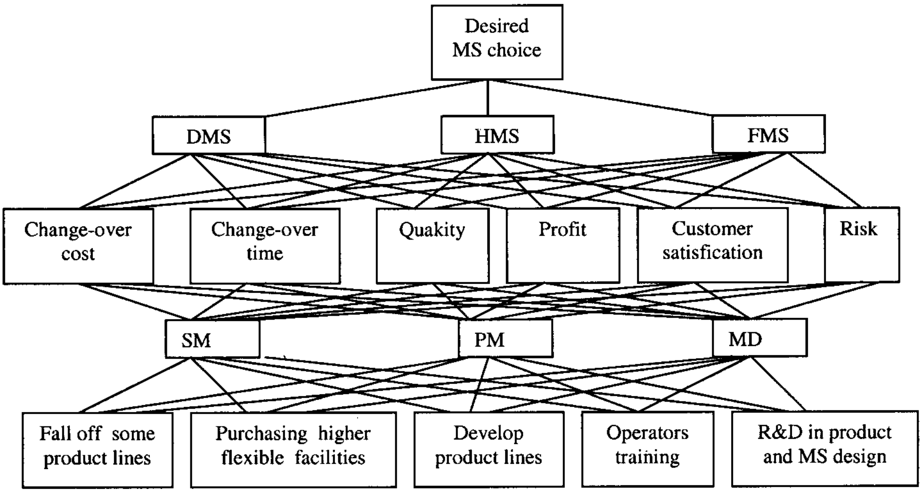

Figure 9. Backward hierarchy for the desired MS choice.

During last few years, the product lines have expanded in response to customer needs and new technology. As different lines have different profits for the company, it is necessary to consider the elimination policy of some of older, less profitable lines and concentrate design efforts on new and competitive products. Another policy in the backward process is 'Research and Development (R&D) at the product-process design' in order to integrate modularity and reconfigurability throughout the whole system.

At the tactical level, the competitive market creates the need for reconfiguring the MS while changing product families. As already mentioned, the selection policy for the families and their assignment to an optimal configuration of a manufacturing system is an active task in the reconfiguration link. The stochastic models and simulation tools can be used to find the optimal configuration for each family considering the changeover time and cost. Xiaobo *et al.* (2000) presented a stochastic model to find the optimal configurations of a RMS when product families arrive with passion distribution functions. In the model, changeover cost was considered whereas changeover time was ignored and assumed to be very short. The state variables for different configurations derived from the simulation results such as change over cost/time can be used for the revision of the AHP model through the forward-backward process. The priorities of state variables in the backward hierarchy can be quantified from the state values of the simulation results. In this manner, tactical design and the design strategy perform a design loop, as already illustrated in figure 2, that not only shortens the reconfiguration cost and ramp-up time but also decreases the risk and uncertainty at the strategic/tactical design and implementation stage.

8. Resource allocation analysis

Once the preferences of alternative manufacturing systems are achieved, the problem is then transferred to how their requirements can meet the resources available. In this regard, a trading off between the derived priorities and required resources for each alternative is essential to maximize the performance of the proposed (re)design strategy. The full details of resource characteristics can be obtained in the tactical design of RMSs, in which the type and number of manufacturing facilities are clearly identified.

One of the effective approaches to resource allocation is the knapsack method, which can be linearly formulated as the following (0–1) integer problem.

$$\text{Max} \quad \sum_{i=1}^{n} P_i X_i \tag{3}$$

subject to:

$$\sum_{i=1}^{n} R_{ij} X_i \leq B_j \tag{4}$$

$$P_i \text{ and } R_{ij} \geq 0 \tag{5}$$

$$X_i = \begin{cases} 1 & \text{if alternative } i \text{ is selected,} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

$$i = 1, \ldots, n,$$

$$j = 1, \ldots, m,$$

where X_i is the ith alternative solution for MS configuration, P_i is the priority of the ith alternative obtained through solving the AHP model, and R_{ij} is the expected amount of jth resource required by the ith alternative. B_j is the available amount of the jth resource at the company. There are n alternatives, which require m resources. The objective is to find the optimal assignment of resources to MS alternatives so that it maximizes the sum of resource utilization. This can justify the selection of the optimal configuration for a specific case under study.

The requirements for the case study are expected to be the budget, for (re)designing the system, the time of the (re)design and the establishment of the system reconfiguration, and the equipment of the selected manufacturing system. As each alternative selection creates a source of risk, the strategic risk level is also considered as another resource parameter for each alternative. The knapsack method can be linked to the manufacturing choices obtained from the AHP model for their resource allocations.

Assuming the matrix of resource requirements for each MS alternative is given, as shown in table 6, the available resources can support the resource requirements for DMS and HMS in the strategic plan. However, the expert/trained operators for RMS cannot be recruited as expected in the strategic plan. In addition, the estimated time of designing a RMS is exactly the upper limit of the acceptable time of (re)design and the establishment of RMS as a new MS. On the other hand, the strategy itself creates a source of risk in the design and implementation of MS configurations. Assuming the risk of the design strategy of RMS (25%) is higher than other alternatives and exceeds the upper allowance limit (20%). The risk of future strategy depends on the current conditions of the manufacturing system and can be estimated by current trends of its influencing factors.

For HMS and DMS, the available resources can cover the resource requirements, but the remaining resources of HMS are not enough to support any other alternative design. For DMS, except for budget, the other remaining resources can also support a HMS design. This may theoretically recommend a recombination of DMS and HMS in which DMS will take more share than RMS. It then appears that, before the implementation of a selected MS at a strategic level, a tactical/detailed design is essential to prepare accurate financial/quantitative data for appropriate decision making.

9. Conclusions and further research

RMSs' characteristics are compared to traditional and conventional manufacturing systems, such as DMSs, CMSs, FMSs, in order to achieve a strategy for selecting the appropriate system over a planning horizon. One of the distinctive features of RMSs, called a 'reconfiguration link', is considered to link the market and the manufacturing system through a design loop. The authors have developed the proposed reconfiguration link, to contribute RMS design in order to group products into families and to select the most preferred product family over each configuration stage.

The strength of the AHP method lies in the multi-period, multi-actors, and multi-criteria structure. Dividing a far planning horizon into a number of periods, such as LT, MT and ST, not only decreases uncertainty and risk over time but also facilitates the analysis of the AHP model from different actors' viewpoints. Although the model might not be adaptable to a number of manufacturing environments, the model appears to be flexible enough to support the strategic justification of a wide variety of manufacturing companies through restructuring criteria according the nature of their organizations.

The reorganization of manufacturing systems and the introduction of new technology can be assisted through the application of the AHP model in which new and classical requirements are taken into account. The proposed criteria contribute towards strategic requirements for RMSs design, fulfilling the lack of a strategic link between technology and business objectives.

The AHP model can be linked to the tactical design of RMSs through the proposed forward–backward process to direct and control the most likely design strategy towards the desired one. The imprecision of judgements can be a result of a lack of accurate values of the backward state variables whose values rank MS choices. Therefore, having matched the state variables of the tactical/operational level of an established RMS, the design strategy can be reconfigured according the values at each time period. Accordingly, simulation approaches can be integrated into the AHP model through matching their state variables. The values derived from the simulation results, such as changeover cost and time, and machine utilization will be applied to quantify the criteria in the backward revision process. This reconfigurable AHP methodology can also be extended to a fuzzy AHP model in order to incorporate uncertainty into the input values.

The example presented in the knapsack model for resource allocations of MS choices is highly simplified. The evaluation between required and available resources, in practice, will be more complicated and needs to be precisely quantified at the next tactical design step.

The authors intend to extend this research at the tactical level for the identification, allocation, and configuration of resources (reconfigurable layout) via a five-step tactical/detailed design. In this respect, the compatible operational techniques in FMSs (e.g. analytical models in machine sharing and flexible layout) and CMSs (e.g. clustering algorithms) will be developed for grouping products into families and in order to assign them to the appropriate configurations.

Acknowledgements

We are pleased to acknowledge the referees for their useful comments which have encouraged us to improve this research work. We also appreciate the support and cooperation of Arvin Meritor company in data gathering through the case study.

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