Selecting next-generation manufacturing paradigms—an analytic hierarchy process based criticality analysis

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Abstract: In the future, manufacturing will be driven by increased competition, sophisticated customer demands and rapid advances in technology. It is therefore necessary to define methodologies for manufacturing that are capable of identifying the driving forces of change and coping with the resultant changes. In this paper, a survey has identified the present trends in manufacturing. Some manufacturing paradigms that have been proposed by researchers have then been investigated. The characteristics and enabling methodologies of these paradigms have been discussed. The criteria that justify a suitable manufacturing paradigm for the twenty-first century have been represented in a hierarchy model based on the analytic hierarchy process (AHP). This decision tool was used to identify the paradigm with the highest ranking for future implementation. In the last section of the paper, a sensitivity analysis has been carried out to observe the effects of varying the priorities of different criteria.

Keywords: next-generation manufacturing, analytic hierarchy process (AHP), criticality analysis, manufacturing paradigms

1 INTRODUCTION

Globalization of the economy and expansion of industrialization to developing countries has been taking place at a steady pace in recent years. However, in order to compete in such a dynamic environment, it is necessary to define a set of rules or paradigms that dictate the changes that need to be made to achieve this goal. The different paradigms that have recently been proposed for manufacturing in the twenty-first century are analysed and compared in this paper. The present trends that define the manufacturing of today have led to the development of these paradigms.

The selection of a suitable paradigm can be made using the analytic hierarchy process (AHP) developed by Saaty [**1**]. It is useful for comparing qualitative as well as quantitative criteria. The accuracy of judgements made in the AHP is ensured by measures of inconsistency which must be kept below a particular value. A sensitivity analysis can also be performed to observe the effects of varying the priorities of certain criteria.

2 PRESENT TRENDS

The manufacturing methodologies of today are defined by the way companies and organizations compete in the global environment. There has been considerable improvement in technology and manufacturing strategies since the industrial revolution. Employee factors such as job satisfaction and wages have improved significantly over time. Product lead times have decreased and there have been major improvements in product quality characteristics. The effects of modernization have led to an increase in global productivity. Yoshikawa [**2**] describes the affluence of modern society largely as a result of increased productivity. With the emergence of new companies and organizations intending to benefit from higher productivity, global competition has increased rapidly. Factors which are a result of present trends in manufacturing are described below.

1. *Market responsiveness*. Competition has increased tremendously since the industrial revolution. This has

The MS was received on 24 August 2000 and was accepted after revision for publication on 12 April 2001.
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been dictated by the rapidly changing market demands. Due to advancements in new technologies, customers have become more sophisticated in their demands. To cope with these rapid changes, organizations are trying to get a product to market as fast as possible; they are focused on product development. A business principle that emerged in the 1990s is: 'The market is changing so rapidly that if you cannot change, you only become a loser, but if you continue to produce the same products, you become a great loser' [3].

2. *Poor product utilization*. Due to increased competition, products are being introduced in the market rapidly, sometimes before the customer demands them. It is a natural phenomenon that a new product will replace an existing product that is in its maturity stage. However, if products are introduced at a faster rate, existing products are phased-out without fully utilizing their useful product life. This has led to products having shorter life cycles and is a major factor causing customer sophistication.
3. *Product and systems complexity*. Increased competition has led to added complexity in products which customers have difficulty dealing with. Constraints imposed by human capabilities have posed a problem for people dealing with large and complex products [3]. This has led to some companies making more profit from servicing their product rather than from sales.
4. *Environmental concerns*. For the purpose of manufacturing, natural resources are consumed, most of which are non-renewable. By-products of manufacturing are released into the surroundings and may cause damage to the environment. Natural resources are limited, and unless measures are taken to replace them, the concept of mass production emphasis on productivity and profitability will cease to exist in the near future and global productivity will greatly decrease.
5. *Lack of knowledge integration*. Manufacturers devote more time to achieving higher productivity than they do to research and development. This leads to inefficiency in operations and greater uncertainty in the organization. Weston [4] has outlined that uncertainties result due to three factors: (a) insufficient information; (b) information being unreliable and (c) contrary opinions of experts. Machinery and hardware alone are insufficient for developing a competitive environment; the methodologies embodied within an organization and applied via a trained work force are necessary [5].
6. *Need for functional and process integration*. Integration of processes is a key issue which is playing a major role at present and will also be vital in the future. Flexible manufacturing systems (FMS) and computer integrated manufacturing (CIM) are examples of process integration scenarios that are used today. It is also necessary to integrate the various business disciplines in a concurrent engineering approach.
7. *Modelling and simulation techniques*. Modelling techniques are already in use today to simulate manufacturing environments, but their use is limited to specific enterprises. As advances are made in new technologies, it is becoming increasingly necessary to model them before implementing them. Such techniques are also required for measuring performance during operations.
8. *Increased technology replacement*. There is a tendency to ignore long-term strategies and focus on present trends. People spend more time reacting to market pressures and devote less time to the research and development that is necessary for innovation and future survival [6]. Increased global competition has demanded that existing technologies in organizations should be capable of adapting to market changes. Old technology is being replaced by more advanced technology to cope with this situation. However, as markets become even more sophisticated as the present trends indicate, it will not be long before these technologies are also replaced. It is also vital that new technologies should be compatible with existing systems.
9. *Team-based organizations and employee skills*. Several organizations, especially those in the West, attribute little importance to the team philosophy. This has caused barriers to build-up within organizations and has had a negative impact on knowledge acquisition and company integration issues. As advances in technology are made, there is a greater demand for employees to have multidisciplinary skills.

The factors described above play a significant role in defining the requirements for a next-generation manufacturing paradigm. They may be expanded to include other critical criteria such as higher productivity, lower waste generation and recycling of wastes/used products. Figure 1 shows how these criteria can be classified into four general categories.

3 WHAT IS A PARADIGM?

In this paper, five paradigms that describe proposed future manufacturing methodologies will be discussed in detail and will be compared using the AHP. However, first it is necessary to understand what a paradigm actually is. Towill [7] has provided a few key points which state that a paradigm:

(a) is a set of rules which establishes boundaries and describes how to solve problems within these boundaries,
(b) influences our perception and aids organization and classification of the way individuals see the world,
(c) is a model which aids comprehension of what the individual sees and hears,

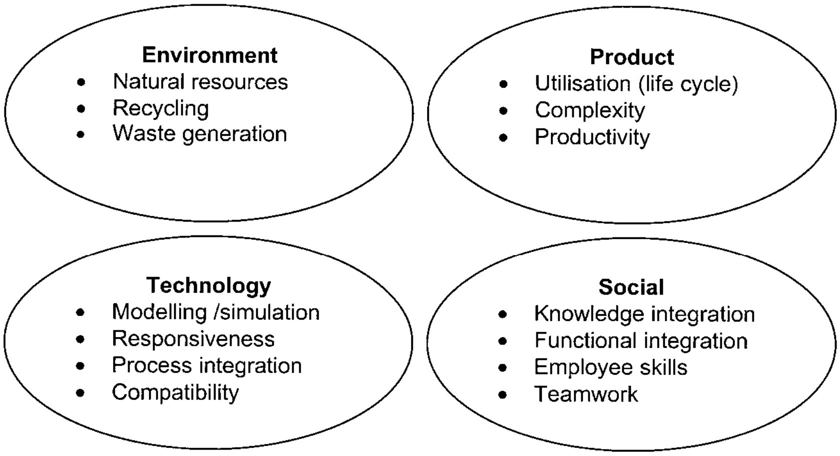

Fig. 1 Classification and description of criteria defining next-generation manufacturing paradigms

(d) may be seen as a set of unquestioned, subconscious business assumptions,
(e) has the effect of a new beginning, i.e. is a new way of doing things.

Before the analysis of some identified relevant paradigms is presented, the authors would like to indicate that they do not claim to be experts in all the paradigms presented. The idea of the paper is not to rank those specific paradigms *per se* but rather to offer a framework, or a methodology, that can help to identify and prioritize next-generation manufacturing (NGM) paradigms by a group of experts and practitioners.

4 PARADIGM 1: A HOLISTIC MODEL-DRIVEN MANUFACTURING SYSTEM

4.1 Objective

This paradigm outlines the future role for holistic model-driven systems, which are capable of responding rapidly to competitive forces and sophisticated socio-political economic change while maintaining good alignment between business goals and related processes and operations. It is based on the 'business process re-engineering' (BPR) concept which is defined by Slack *et al.* [**8**] as the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service and speed.

4.2 Characteristics

The holistic model was compiled by a group of researchers from various business disciplines. Their work has been outlined by Weston [**4**]. The work involved surveying possible manufacturing scenarios for 2005 AD and beyond and identifying barriers that would limit progress in these scenarios considering applications of BPR. The areas covered in the survey were 'likely givens', 'important trends' and 'uncertainties' connected with manufacturing and its supporting systems during the next decade.

Likely givens are things that are constant and change in a way where there is minimal uncertainty, and these include:

(a) critical roles for information systems in manufacturing,
(b) increased need globally for manufactured goods,
(c) greater concern for environmental issues,
(d) more self-employed people,
(e) fully global communication.

A 'holistic' approach requires that each entity of a manufacturing system must be considered simultaneously as a whole. Therefore the interrelationships between the entities is of extreme importance. Responsibilities are usually allotted to the people concerned within each entity and decisions are team based. Before making a decision, Weston [**4**] has stressed that the suitability of company culture, and of the environment in which it operates, should be appraised with respect to its acceptance of devolved responsibility and holistic, team-based decision making. The act of defining and selecting a scenario provides a beneficial way of developing alignment in management teams through ownership of ideas; this is imperative for successfully adopting a holistic approach and forms the basis of BPR.

Work on formulating a holistic approach was also done earlier by Pandya *et al.* [**9**], who described an organization adopting the holistic approach as a process-based organization rather than a functional one. It is necessary to manage and improve processes continuously and to perform re-engineering projects when needed.

The primary focus of BPR is the belief that operations should be organized around the total process, which adds value for customers, rather than the functions or activities that perform the value-adding activity (Slack *et al.* [**8**]). BPR programmes can be carried if there is availability of a broadly understood and agreed vision of future need. When determining a suitable enterprise in the context of BPR, technical, structural and environmental issues also need to be considered. To establish BPR, companies need to understand the strengths and weaknesses of their key business processes and to benchmark their capabilities against their competitors. Business analysis concepts like these can lead to the holistic redesign and reconfiguration of an enterprise.

Faster BPR allows project implementation within time scales which are congruent with typical rates of change found in operating environments. It is also vital to enable BPR in increments. Moving incrementally via a series of 'quick wins' towards the holistic goal allows adequate time for changing the configurations of previously installed systems. There are some factors which are a hindrance to the implementation of a holistic approach to manufacturing. Some are due to the inherent risk or fear of change which is analogous to the implementation of any system. Unfamiliarity with BPR is another reason, together with problems associated with deploying new technology. Two main barriers for BPR implementation outlined by Weston [**4**] are:

1. Complex and interrelated difficulties associated with inherent organizational and cultural factors, systems integration factors, financial constraints, lack of technical skills and software development issues.
2. Difficulties of remaining competitive while seeking to change the configuration of an enterprise and its underlying systems and the relatively long lead times associated with specifying and implementing change to information technology (IT), cultural and organizational systems.

4.3 Enabling methodologies

Pandya *et al.* [**9**] have outlined certain methodologies that can help in achieving the objectives of this approach.

1. The 'order fulfilment process' transforms product orders and information into products that satisfy customer requirements. It is capable of fulfilling orders in an 'elastic' enterprise where the product volume is variable. It is also flexible to cope with orders where product variety is involved using the same processes and equipment in a 'flexible' enterprise.
2. The 'marketing process' transforms information from markets, competitors and customers into market requirements. It performs activities that include foreseeing product volume and variety changes. This enables the organization to have a better reputation in the market hence initiating customer orders.
3. The 'support fulfilment process' transforms a need for support and service into a product that continues to meet customer demands. The 'obtain order process' transforms customer/market requirements into product/service orders. Both these processes are customer oriented and enable long-term relationships.
4. For companies concerned with creating an innovative climate, developing new products and reducing lead times, the 'product and service development process' and the 'technology management process' are used. The former transforms customer/market requirements into product information. This provides an integrated knowledge base that can be accessed by all functions. The latter deals with transforming data from research and competitors into technology knowledge and information.

This paradigm also involves modelling tools that can be used for IT and business integration. For the planning and execution process of a design, such tools are used for strategic planning, conceptual design and detailed design. Similarly, tools and software methodologies are available to model the structure and behaviour of an enterprise, function, organization or resource. Modelling tools must be capable of supporting specialization of generic models by utilization of knowledge that is specific to a particular domain or enterprise.

5 PARADIGM 2: THE POST-MASS-PRODUCTION PARADIGM (PMPP)

5.1 Objective

The post-mass-production paradigm (PMPP) is a system of economic activity capable of encouraging and sustaining economic growth without depending on mass production and mass consumption of artefacts. The aim is to formulate a paradigm that allows product life cycles to be fully utilized, with input resources being used efficiently and then being recycled. It is an attempt to limit the rapidly changing systems of today and realize that the earth is bounded and not limitless in its resources.

5.2 Characteristics

This paradigm was introduced by Tomiyama [**3**]. PMPP was introduced to tackle the problems encountered due to the social and economic backgrounds of manufacturing. Mass production has been considered as a competitive weapon, but this has led to useful product life cycles of relatively short length. Environmental impacts such as natural resource depletion and waste generation have increased proportionally. PMPP represents a transformation from the quantitative sufficiency of artefacts to qualitative satisfaction. It is meant to remove the modern evils of mass production and create a knowledge-intensive society.

PMPP aims at maximizing global productivity while maintaining individual corporate/regional/national productivity and arriving at global sustainability. It provides mechanisms for economic development based on the creation of high-value products that depend on intellectual resources rather than natural resources. It also reflects on the concepts of BPR. This paradigm has defined the manufacturing industry as a 'life-cycle' industry. The present manufacturing industry provides services from marketing through maintenance; however, reclamation, recycling and discarding of waste are normally outside the common domain of the manufacturing industry.

Hitomi [**10**] has stressed the importance of 'manufacturing excellence'. This has been described as the enhancement of the suitability of goods production for pursuing human happiness while being rid of excess production, de-industrialization and earth-destructive operations. The concepts of human-centred production, responsive manufacturing and recyclability for resource saving and environmental preservation are similar to those of PMPP.

5.3 Enabling methodologies

1. The life-cycle industry is proposed to involve reclamation and recycling as manufacturing activities, the cost of which can be added to the product, but with positive consequences for the environment. Recycling can be facilitated with cutting-edge technologies such as nanomachining and biotechnology. In a knowledge-intensive society, reclamation and recycling are considered as material acquisition activities.
2. Knowledge-intensive engineering is a concept involving marketing, design, production, logistics, operations, maintenance, reclamation, reuse, recycling and discarding. It is a new way of engineering activities in various product life-cycle stages conducted with more knowledge in a flexible manner to generate more added-value proposed through PMPP [**3**]. PMPP is viewed as a survival strategy for the twenty-first century in which knowledge will play increasingly crucial roles unlike today. BPR is based on acquiring knowledge as a commodity for manufacturing technology.
3. Soft artefacts are elements that can generate more added-value with accumulated, intensive knowledge about product life cycle to compensate for a decrease in production volume. They exhibit features including autonomy, self-organization, self-maintenance and reconfigurability based on intelligence and modularity. Soft artefacts are based on three principle strategies:

   (a) Longer life and high reliability of artefacts during their lives;
   (b) More added-value generation through a product's life cycle (e.g. lift and photocopier manufacturers gain more profit from maintenance and servicing of their products than from sales) and from multiple use of used artefacts (after reclamation and recycling);
   (c) Fair evaluation of life-cycle cost (product price includes reclamation and recycling costs).

Soft artefacts are of two types: social capitalized artefacts and growth sustaining artefacts. Social capitalized artefacts still aim at quantitative sufficiency, but are completely recyclable and reusable, forming an item of social capital. Growth-sustaining artefacts are high-value products that aim to achieve qualitative satisfaction. They can be upgraded when needed due to their modular structure. Examples of soft artefacts are self-maintenance machines which are self-reconfigurable to allow functionality of the most critical functions and are based on intelligent design, and cellular machines which have a modular structure and each cell has a central processing unit (CPU) embedded in it to exhibit highly autonomous-based intelligence.

6 PARADIGM 3: ULTIMATE MANUFACTURING

6.1 Objective

Issues concerning the rate of technological change, market globalization and corporate social responsibility are considered here to impact on the future of manufacturing industries. This paradigm includes methodologies to optimize these issues so that they are compatible with the needs of the future.

6.2 Characteristics

Wah [**6**] has described how today's manufacturers have been facing increased global competition and pressure to get products out faster. They want to excel as customer-centred enterprises that develop congenial relations with customers and suppliers to manage the flow of knowledge to all parties. Flow of information takes precedence over the flow of materials. Future enterprises will involve as little physical material handling as possible. Simulation models have the capability to make interactions between material flow processes error-free with the application of proper logistics.

Future trends need to be analysed differently. The essence of competition in the future is creativity and innovation rather than productivity. Cost effectiveness in operations as well as faster lead times will still be trends applicable to future enterprises, but research and development must also be considered since this plays a vital role in the development of future manufacturing methodologies. The ability to respond to customers, cultures and the global market will determine the success of manufacturers in the future. They will also need to be flexible in their use of human resources and equipment if they want to have a competitive weapon.

The Committee on Visionary Manufacturing (The National Research Council) has published a book entitled *Visionary Manufacturing Challenges for 2020* [**11**]. It outlines some manufacturing challenges that the world is expected to face in the early twenty-first century; enabling technologies have also been analysed. Among the forces dictating changes for the future, as outlined in the text, the need for global distribution is stressed as well as creativity and innovation being the prerequisites for competition. The importance of human and technological integration necessary for research and development are also mentioned. These factors also build on the concepts of ‘ultimate manufacturing’ described by Wah [**6**].

Barriers to achieving ultimate manufacturing involve a number of issues. Although innovation is the key to survival, enterprises are facing challenges that were non-existent a decade ago, such as high productivity and shorter product life cycles as well as the burden on the environment. Many organizations are isolating themselves from research and development, concentrating more on short-term customer responsiveness methods. Developed nations are slow in transferring technologies such as just-in-time (JIT), total quality management (TQM) and lean manufacturing to developing countries which are capable of managing such technologies. This gives these nations less time for research and development of innovative methodologies.

6.3 Enabling methodologies

The four main areas where manufacturers need to excel are in customer, global market, plant and equipment, and human resource responsiveness [**6**].

6.3.1 Customer responsiveness

1. Logistics management technologies to obtain a sound knowledge base from customers and suppliers throughout the supply chain. This also includes end-users.
2. Teaming and willingness to share knowledge.
3. Real-time knowledge from enterprise customers and customers’ customers.
4. Creating low-cost designs capable of reaching the market quickly.
5. Virtual manufacturing technologies to allow access to distributed models so that modifications to designs, costs and cycle times can be made.

6.3.2 Global market responsiveness

1. Research and development must be geographically dispersed.
2. Truly innovative companies tap knowledge from all possible resources.
3. Globalization of the enterprises’ economy.

6.3.3 Plant/equipment responsiveness

1. Flexibility in equipment use.
2. Minimizing assets to meet existing demand and expanding production capacity to cope with flexibility.
3. Leased/reconfigurable equipment.
4. New technologies such as virtual manufacturing, micromachining and biotechnology.
5. Elimination of expensive jigs and fixtures with the advent of molecular machining processes.
6. Simulation techniques integrated with logistics control systems to model real-life configurations of machinery and production units.

6.3.4 Human resource responsiveness

1. Having a trained multidisciplinary workforce with enhanced skills.
2. Ability to create and innovate new products.

In addition to achieving responsiveness, other elements, as outlined in reference [**11**], for establishing ‘ultimate manufacturing’ are:

3. New materials processing for enhanced creativity.
4. Information technology to improve research and development capabilities.
5. Enhanced human–machine interfaces enabling human/technical integration.

7 PARADIGM 4: PARNABY’S MILLENNIUM APPROACH

7.1 Objective

This methodology, proposed by Parnaby [**5**], is aimed at exploring the roles of technology and management in setting up a manufacturing facility that has the capability to be competitive in world markets in the twenty-first century. It is centred on efficient use of the human resource in team-oriented frameworks for effective use of the most appropriate technologies; it also aims at reducing complexity.

7.2 Characteristics

In recent times, the performance of companies has shown that the traditional bureaucratic, specialized structures are not capable of facing emerging competitive organizations. To tackle this problem, organizations are being designed to make more effective use of their employees, using new forms of discipline, which facilitate new methods of creative value-adding engineering. Technology is a means of improving performance in core business areas, but this has been a low priority in business management's perception. This led to the failure of organizations in the 1980s. The negative effects were visible through:

1. Capital investments, which were meant to 'automate out' people, but this led to increased equipment servicing costs and, as a consequence, potential financial returns were negligible.
2. Complex equipment acquired through this process was complex and unreliable and could not be maintained effectively to ensure cost effective usage and high productivity.
3. Equipment was too inflexible to adapt quickly and cheaply to market changes.

In the 1990s it was realized that a total engineering approach was required for total factory design. This required a model where each element or subsystem fits effectively in a system as a whole, organized and operated on modern lines using the most appropriate technologies, not necessarily the most advanced ones [**5**]. The building blocks to achieve such methodologies exist today and are:

(a) cross-functional organizational design and control (e.g. CIM, concurrent engineering);
(b) clear focus on more effective design operation and control of lean, low-waste, team-operated core business processes;
(c) heavy focus on working cell team organization structures, with each team trained in the required operational methodologies;
(d) simplification, using the tools of systems design and operation to cut out complexity, variability and non-value-adding activities.

7.3 Enabling methodologies

These methodologies for building the factory of the twenty-first century have been outlined by Parnaby [**5**]:

1. To achieve rapid progress, company leaders must consider manufacturing development simultaneously with product development. The product characteristics determine the type of manufacturing facility. This is the only way technology innovations can lead to reliable exploitation and financial success for the company.
2. Formalized change to the project management structure is also vital to ensure that needs are professionally planned and specified. This will match business strategies so that innovations are effectively managed to achieve rapid ordered progress across many simultaneous initiatives.
3. Operational competencies such as manufacturing, maintenance and project management are just as important as development competencies such as control systems and software engineering. Adding IT to an already complex and wasteful organization adds another layer of complexity that makes the simplification process difficult.
4. Structural development of people is important and involves competence-focused training, job rotation and project team experience, together with technical, operational and commercial management training.
5. The real value of a company lies in the know-how that it contributes to its processes. Value-adding know-how such as software control, proper interfacing, on-line process capability measures, total productive maintenance (TPM), and computer aided design (CAD) links have a positive effect on lead time and stock levels in competitive organizations.
6. Unique, hard-to-copy value-adding activities.
7. Reducing complexity by developing generic modular hardware and software designs, reducing the number of components in a product for easier assembly, saves inventory, quality and purchasing costs.
8. Avoiding overengineering and unwanted complexity, and making technology more user friendly.

Parnaby [**5**] emphasizes the importance of meeting requirements through available methodologies to minimize costs and implementation times. To efficiently make use of human resources in research and development, the National Research Council [**11**] has outlined a methodology for interdisciplinary research:

(a) identify current problems,
(b) articulate problems to academics in research institutes,
(c) facilitate the formation of integrated research teams,
(d) articulate the technical results to the relevant business functions.

8 PARADIGM 5: INTELLIGENT MANUFACTURING SYSTEMS (IMS)

8.1 Objective

The intelligent manufacturing system (IMS) paradigm was developed in 1995 by the Japanese and is now being developed with the collaboration of other countries. It emphasizes the sharing of technologies between organizations and nations to encourage them to work together to achieve an improved global manufacturing environment [**2**, **12**].

8.2 Characteristics

In the mid-1980s, Japan was producing high-quality products at significantly lower costs compared with other developed nations. However, developed nations argued that the Japanese had stolen their technology and applied it in an improved manner to achieve this. This later became a hindrance for the acceptance of their products and ways. It was also discovered that present production systems were restrained by limitations such as environmental concerns. The fact that 15 per cent of the world's productivity is provided by Japan was amazing for a country that occupies only 0.3 per cent of the world's land area. However, this figure was showing no further increase at this stage which indicated that a change was required. The Japanese realized that a global paradigm shift was necessary [**2**]; this realization paved the way for the IMS concept.

The IMS Research Group [**12**] outlined the reasons for initiating IMS:

(a) to enable greater sophistication in manufacturing operations,
(b) to improve efficiency of renewable and non-renewable resource use,
(c) to create new products and conditions that significantly improve quality of life for users,
(d) to improve the quality of the manufacturing environment,
(e) to develop a recognized and respected discipline of manufacturing to encourage the transfer of knowledge,
(f) to enlarge and open markets around the world.

IMS stresses cooperation in research and development for manufacturing technologies of the future. This is expected to normalize competition while solving the problems associated with the conventional competition of today which results in damage to the ecosystem and wastage resulting from excessively short product life cycles (i.e. new product development ahead of consumer wants).

Productivity has brought affluence to the people, but will be short lived due to limitations such as those mentioned above. Global productivity will fall in the near future if no action is taken. Duplication of research, development and investment by individual companies will do nothing for global productivity unless it is carried out in collaboration with other organizations and nations. Yoshikawa [**2**] has described knowledge as being of three types in the IMS concept in order to compete in a market environment: (a) rules of the game—making it possible to compete; (b) common body of knowledge—making it possible to manufacture; (c) confidential knowledge—required to provide a competitive edge. In a free economic system, secret knowledge that is kept by a company for competitive reasons is only a small portion of the total knowledge, the majority of which is shared with other organizations.

7.3 Enabling methodologies

IMS is being considered worldwide because of its potential as an emerging global paradigm. Factors that have led to this conclusion are:

1. *Product life cycle issues*. These involve proposals for future models of manufacturing systems, intelligent communication network systems, optimum use of energy and materials, recyclability and refurbishment, and economic justification methods.
2. *Process issues*. These issues realize the need for rapid responses to changing requirements, saving human and material resources and improving working conditions for employees. Factors addressing these issues are clean manufacturing processes, energy efficient processes, technological innovation in manufacturing processes, improvement in the autonomy and flexibility of processing modules (i.e. holonic manufacturing), and increased interaction between the various manufacturing disciplines.
3. *Human/organizational/social issues*. These address development projects for improved image of manufacturing, improved capabilities of the workforce through education/training, autonomous offshore plants, corporate knowledge base and appropriate performance measures.
4. *Strategy/planning/design tools*. These are tools such as methods of obtaining and transforming raw materials, business process re-engineering, modelling and simulation techniques.
5. *Collaborative research and development*. Manufacturing is a primary generator of wealth and is critical to establishing a sound economic basis for economic growth. The need for excellence in manufacturing operations has become critical as a result of the establishment of global markets. The role of research and development in the field of advanced manufacturing is increasingly pivotal to manufacturing operations. Substantial research in advanced manufacturing is being carried out world-wide. Properly managed international cooperation in research and development in advanced manufacturing can help improve manufacturing operations [**12**].

9 SELECTING A MANUFACTURING PARADIGM

The fundamental characteristics of five manufacturing paradigms that have been proposed by researchers for application in the twenty-first century have been analysed. In order to select the most appropriate one, it is necessary to consider the criteria and subcriteria that define the goal in an AHP approach. Table 1 shows the criteria that can be used for judging between the available alternatives. The subcriteria have been defined from the present trends taking place in the manufacturing industry. These were classified in four categories as shown in Fig. 1. The categories can be expressed as the main criteria for selecting a next-generation manufacturing paradigm. Therefore they can be included in

Table 1 Judgement criteria for paradigm selection

Criteria (level 1)	Relative ranking*	Subcriteria (level 2)	Relative ranking*
Environmental concerns	M	Natural resource depletion	H
		Waste generation	L
		Recyclability of product/wastes	M
Product issues	H	Product life cycle	H
		Productivity	M
		Complexity	L
Technological factors	M	Equipment responsiveness	VH
		Process integration	H
		Equipment compatibility	L
		Modelling and simulation	M
Social factors	L	Knowledge integration	M
		Functional integration	H
		Employee skills	M
		Team-based approach	L

*VH, H, M and L represent very high, high, medium and low respectively.

level 1 of the hierarchy model. In Table 1, the subcriteria have been ranked according to their influence on the criteria that they represent.

The judgement rankings are estimates of the importance of each criterion relative to each other. The rankings are made based on the authors' knowledge, experience and preferences relating to these paradigms. However, the proposed model can accommodate other opinions based on the knowledge of experts and strategists. Therefore, the authors' judgements were based on the argument that product issues are the most important since they reflect the output of the manufacturing process regardless of the methodology. It is the product-related issues that determine the success of a company. Environmental factors are becoming increasingly important since they are the constraints to continuing manufacturing as it is today; technology factors are equally important. Social factors are also crucial, but of less priority compared with the other criteria. The subcriteria have also been ranked according to relative importance. The main environmental concern is the limitations imposed by natural resources. Recyclability is the next concern because it aims to replace depleted natural resources. In product issues, it may be argued that productivity is the highest priority. However, this alone does not dictate a prosperous organization. The product life cycle must be fully utilized to relieve the burden on the environment; quality of product is a vital concern. For responding to rapid market changes, equipment responsiveness is the most important technological factor. Functional

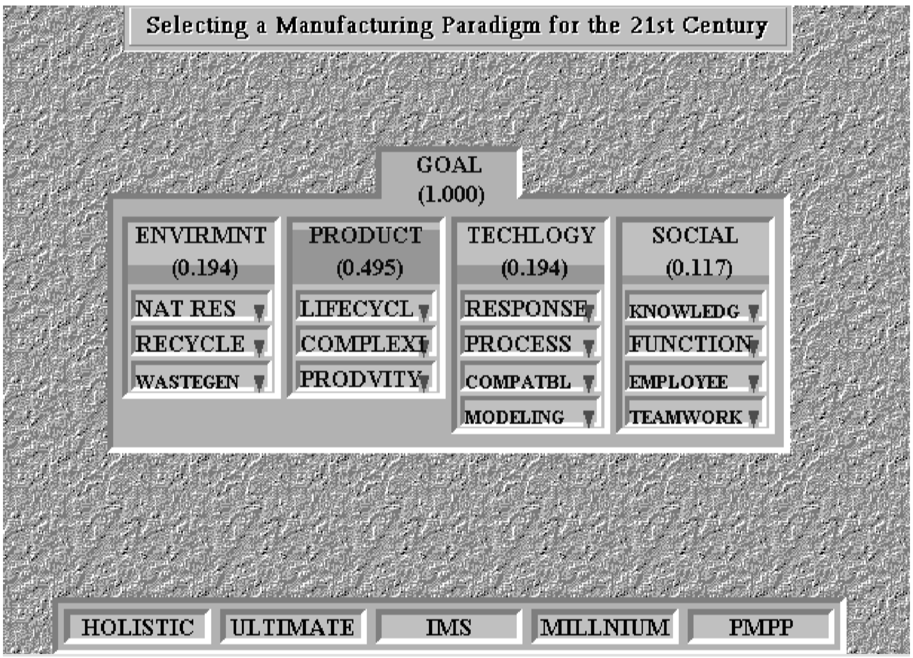

Fig. 2 AHP model for selection of a manufacturing paradigm

integration dictates the concurrency in operations as it is ranked the highest for social factors. Knowledge integration is also playing a crucial role as technologies become more advanced.

The AHP decision model obtained using Expert Choice software is shown in Fig. 2. It has been used to make pairwise judgements among the criteria and subcriteria to select a suitable paradigm. Costs have not been included in the hierarchy because it is difficult to anticipate without further research. Figure 3 shows the AHP model in hierarchical form. The calculated priorities are indicated in the boxes for each criteria, subcriteria and alternative.

It should be noticed that the AHP selection model is based on the classification shown in Fig. 1 and this classification is based on the experience and knowledge of the authors of this work. Hence, they are not comprehensive as it could be claimed that additional criteria

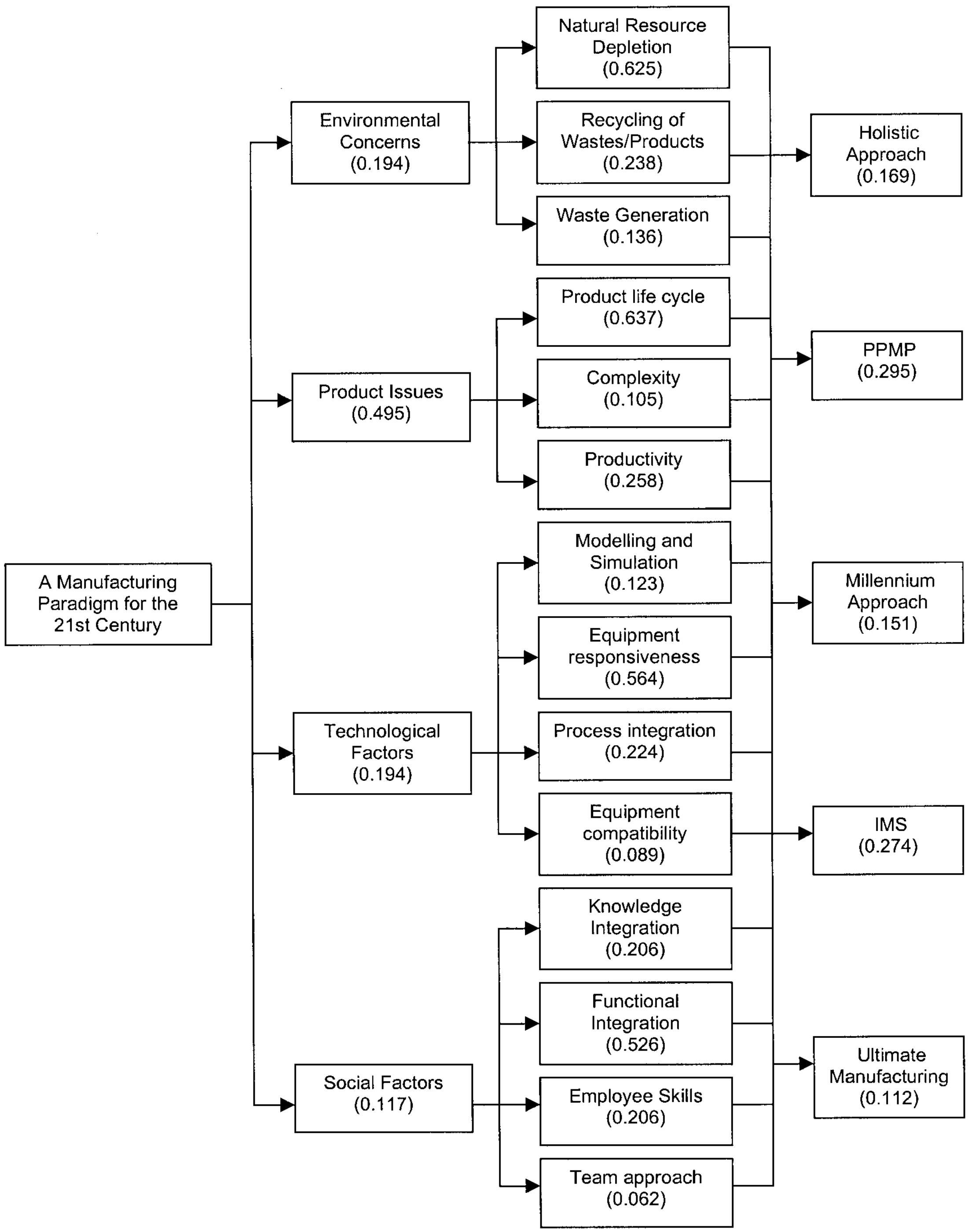

Fig. 3 AHP model showing local priorities

Table 2 Description of subcriteria*

Subcriteria	Description	PMPP	IMS	HOL	ULT	MIL
Reduced natural resources depletion	This indicates the necessity of a paradigm which causes the least depletion of natural resources available or uses renewable resources	VH	H	M	L	L
Recycling of wastes/products	This is a methodology for recycling the by-products of production as well as reusing extinct products to replenish natural resources	VH	H	L	L	L
Less waste generation	Reduced waste generation can be achieved using renewable resources or modifying manufacturing methods (e.g. biotechnology) so less waste is generated	VH	H	M	L	L
Longer product life cycle	Present trends indicate short product life cycles; the product is discarded before full utilization; this unnecessary wastage can be prevented	H	H	L	VL	L
Reduced product complexity	Unnecessary complexity makes the product less user-friendly and more difficult to maintain; it also causes more sophistication in customer demand	M	M	L	L	H
High productivity	This is the aim of every organization, but it should not be at the expense of quality	L	M	H	M	VH
Equipment responsiveness	To respond to the dynamic market, it is necessary that plant equipment and processes are capable of readily adapting to unexpected and rapid changes	M	L	L	VH	H
Process integration	This involves all processes being considered simultaneously in design and planning stages; it reduces uncertainties that may occur during implementation and production	M	L	VH	L	H
Equipment compatibility with existing systems	New equipment and systems should be implemented in stages so that existing systems can be upgraded or replaced with the passage of time; this reduces total down-time	L	L	H	VH	M
Modelling and simulation	Modelling techniques allow simulation of a manufacturing process before implementation and for monitoring it during operation	L	H	VH	M	L
Knowledge integration	Knowledge plays a crucial role in organizations; it must be fully integrated into manufacturing planning, control, design and research to achieve the optimum strategies	H	H	M	VL	L
Functional integration	Traditionally, enterprise management was less concerned with technology and research and development; it is necessary for all business functions to work together to formulate future strategies	VL	M	H	L	M
Employee skills	The rapid rate of technology advancement calls for greater skill capabilities; employees can be taught multidisciplinary skills through appropriate training and job rotation	M	H	L	L	M
Team-based approach	Decisions and strategic planning and control to be carried out in teams; future decisions will be more complex than today due to the technological and market changes	VH	M	L	VL	H

*PMPP, post-mass-production paradigm; IMS, intelligent manufacturing systems; HOL, holistic paradigm; ULT, ultimate manufacturing paradigm; MIL, millennium approach.

need to be considered such as political or economic issues or consideration of issues related to the geographical distribution of business and markets.

The paradigms described all have different aims. Table 2 describes each of the subcriteria. The alternative paradigms have been ranked with each subcriterion. These judgements only reflect the importance of each subcriterion in implementing the individual paradigms. IMS and PMPP are more concerned with reducing competition. They argue that there will be a drop in global productivity if technological advances continue at the present rate, a major reason being the rapid depletion of natural resources. PMPP stresses the importance of knowledge integration in all functions. The millennium and holistic approaches are also concerned with knowledge integration as well as functional integration. Reducing non value-adding activities is vital. Ultimate manufacturing is centred on increasing responsiveness of all business functions. Multidisciplinary skills of employees as well as teamwork are given importance in the millennium, IMS and PMPP paradigms.

Figure 4 shows the final calculated local priorities for each paradigm with respect to a specific branch of the hierarchical model. Globally, PMPP has the highest priority followed by IMS. Even though PMPP had disadvantages, such as lower productivity, the benefits were derived from environmental awareness, a solid knowledge base and proper utilization of the product. Several concepts of IMS are similar to PPMP. However, productivity is higher, employees have better skills and all business functions are integrated to provide the best output through teamwork and collaboration. Ultimate manufacturing is mainly centred on improving responsiveness. Other major issues such as knowledge integration, environmental concerns and product issues are not given much importance in this methodology. The overall inconsistency index is 0.03, which is well below the maximum allowable value of 0.1 recommended by Saaty [1]. This shows that these judgements are highly consistent.

Judgements in this model are based upon general information provided by the proposed paradigms.

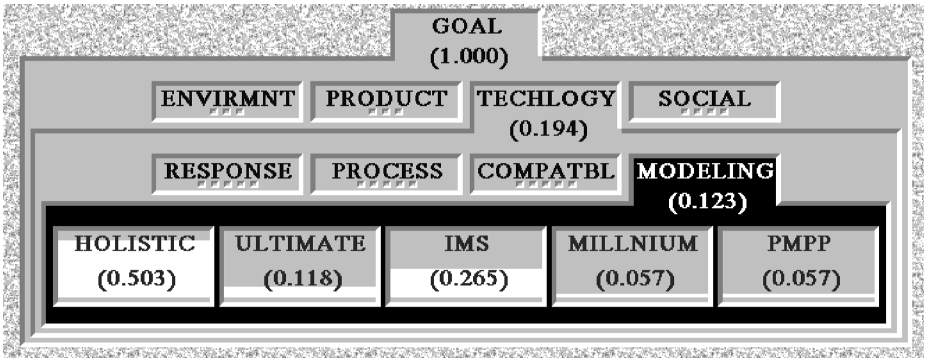

Fig. 4 Local priorities of alternative paradigms

Since research in these methodologies is still progressing, it is difficult to obtain accurate pairwise judgements at this stage unless a survey of manufacturers and enterprises is made.

10 SENSITIVITY ANALYSIS

There is a possibility of changes taking place in the environment, system or market that may render the judgements in this model invalid. Nevertheless, the proposed hierarchy offers a robust framework that models different paradigms. It is an adaptive methodology for prioritization of paradigms and future trends, and can be considered as a modelling representation of a knowledge base. The Expert Choice software incorporates a methodology that will allow use of the original judgements to facilitate any changes. This is the 'sensitivity analysis' which allows the user to vary the priorities of the alternatives, subcriteria and criteria. Any variations will affect the priorities of all the other elements in the AHP model. Since they are all interrelated, the resultant changes can be observed in these elements.

Figure 5 is a dynamic representation of this analysis. The bars on the left are the criteria and those on the right are the alternatives. The bars representing the criteria each have a different pattern. They provide a visual representation of the percentage of importance of each criterion in each alternative. The priorities of any of these criteria can be varied by changing the

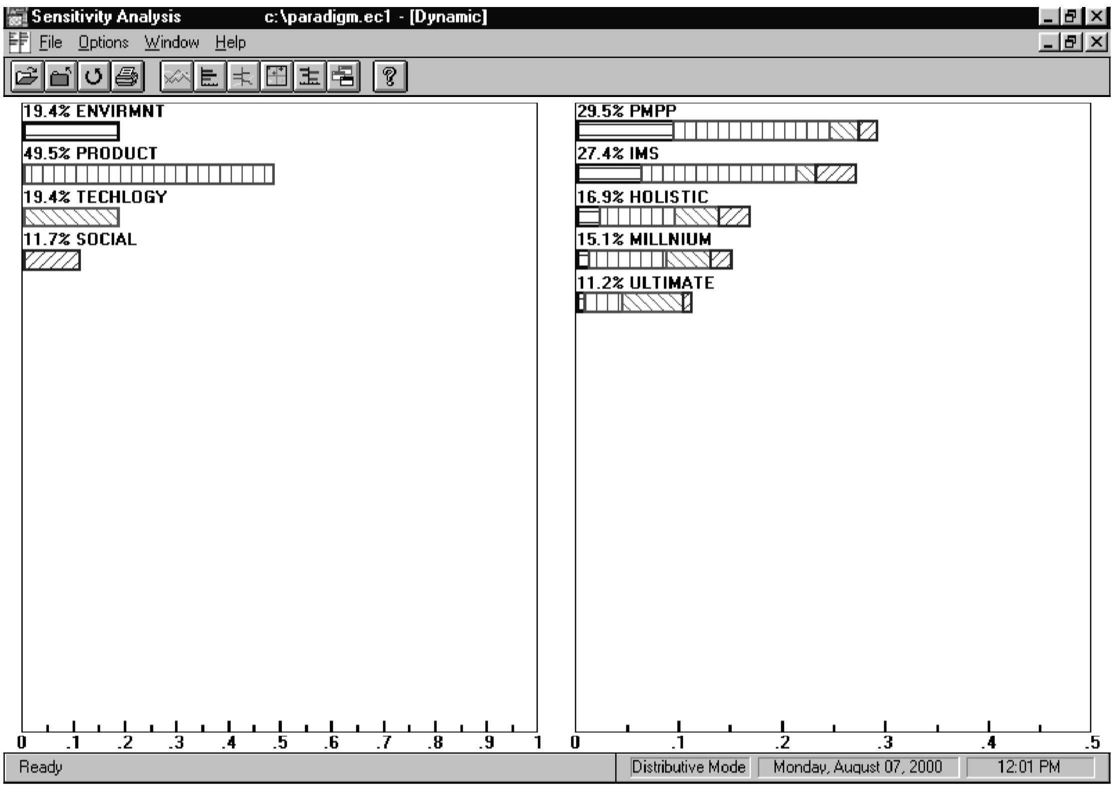

Fig. 5 Sensitivity analysis (dynamic representation)

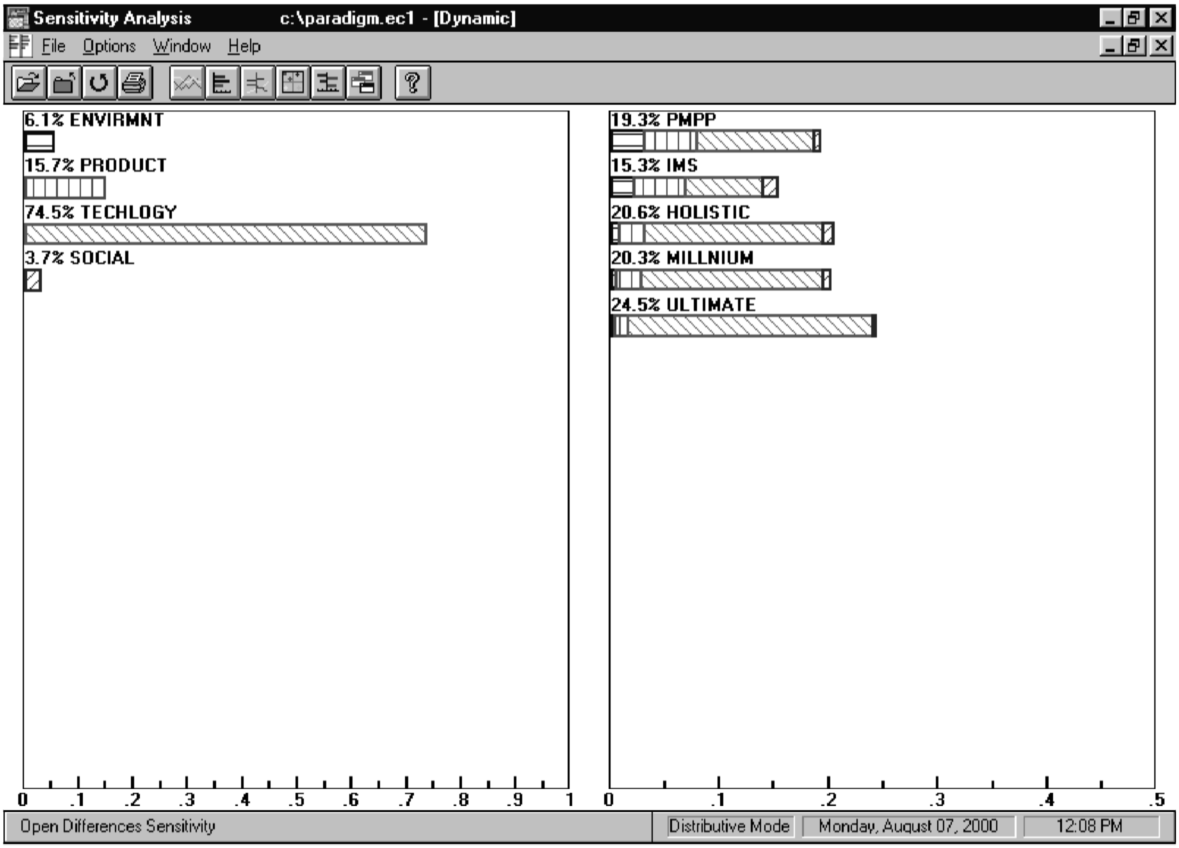

Fig. 6 Sensitivity analysis (modified dynamic representation)

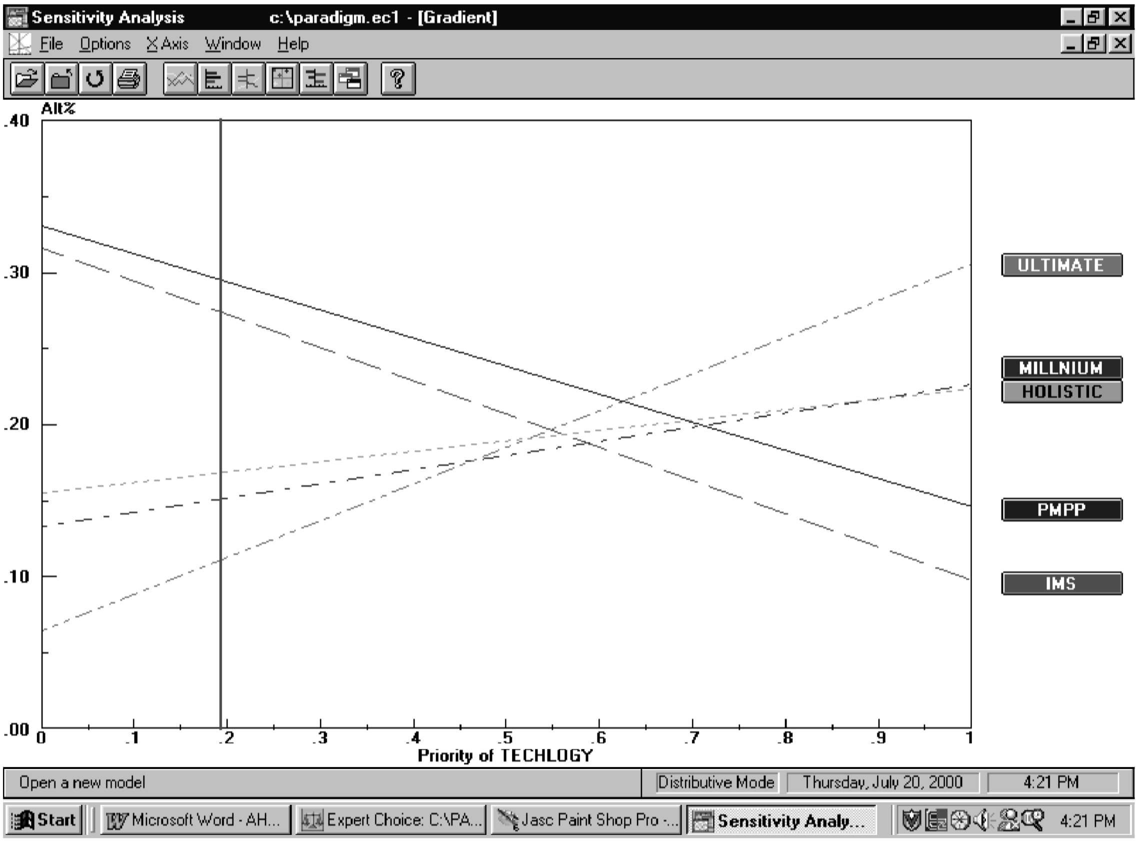

Fig. 7 Sensitivity analysis (gradient representation)

length of the bars, which indicate the priority according to the scale at the bottom. The resultant variations of the other elements can then be observed. For example, if the priority of technology is increased, the most preferred paradigm becomes ultimate manufacturing, as can be seen from Fig. 6. The diagonal pattern of the technology component is the largest for each alternative paradigm.

The gradient representation is another sensitivity analysis methodology. This is shown in Fig. 7. It compares one criterion with each of the alternatives. The vertical line indicates the priority of that particular criterion with respect to the goal. The diagonal lines represent the priorities of the alternatives at each position of the vertical line. Moving the position of this line horizontally results in change of priorities for the alternatives with respect to that criterion. For example, if the line were moved to the right until it reaches a value of 0.65 for technology priority, the point would indicate the intersection of the lines corresponding to the PMPP and the ultimate manufacturing paradigm. This means that both of these paradigms are of the highest ranking at that particular value of priority for the technology criterion. This representation is restricted to the analysis of only one criterion at a time.

11 CONCLUSION

In this paper an attempt has been made to model the various criteria that govern the selection of a suitable paradigm for next-generation manufacturing. The analytic hierarchy process has been used as a decision tool to simplify the modelling procedure. The sensitivity analysis clearly illustrates the interrelationships between the criteria, subcriteria and alternatives and how sensitive they are to variations in priority.

According to the global results obtained from this illustrative example, both PMPP and IMS are the highest-ranking paradigms. Incidentally, both paradigms were proposed by Japanese researchers. Does this result indicate that in the twenty-first century manufacturing paradigms will continue to be exported from Japan to the West and the rest of the world? It is an open question that the authors of this research work offer to the reader to answer and that only time will verify.

ACKNOWLEDGEMENTS

The authors would like to thank the referee for the valuable and constructive criticism. EPSRC funding of this work (GRIM35291) is appreciated.

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