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Agile manufacturing: enablers and an implementation framework

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Tougher competitive situations have led to increasing attention being paid to customer satisfaction, of which timely and customized services are the key concepts. As the product life cycle becomes shortened, high product quality becomes necessary for survival. Markets become highly diversified and global, and continuous and unexpected change become the key factors for success. The need for a method of rapidly and cost-effectively developing products, production facilities and supporting software, including design, process planning and shop floor control system has led to the concept of agile manufacturing.

Agile manufacturing can be defined as the capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services. This article details the key concepts and enablers of agile manufacturing. The key enablers of agile manufacturing include: (i) virtual enterprise formation tools/metrics; (ii) physically distributed manufacturing architecture and teams; (iii) rapid partnership formation tools/metrics; (iv) concurrent engineering; (v) integrated product/production/business information system; (vi) rapid prototyping tools; and (vii) electronic commerce. A conceptual framework for the development of an agile manufacturing system and future research directions are presented in this paper. This framework takes into account the customization and system integration with the help of business process redesign, legal issues, concurrent engineering, computer-integrated manufacturing, cost management, total quality management and information technology.

1. Introduction

The agile manufacturing enterprise can be defined along four dimensions: (i) value-based pricing strategies that enrich customers; (ii) co-operation that enhances competitiveness; (iii) organizational mastery of change and uncertainty; and (iv) investments that leverage the impact of people and information. That is, agility has four underlying principles: delivering value to the customers; being ready for change; valuing human knowledge and skills; and forming virtual partnerships. Agility is a new system of commercial competition, a successor to the still dominant system that was developed around mass production-based competition once it was coupled to the modern industrial corporation. Like the latter, agility was made possible by the synthesis of innovations in manufacturing, information, and communication technologies with radical organizational redesign and new marketing strategies. Moreover, agility is a comprehensive, strategic response to fundamental and irreversible structural changes that are undermining the economic foundations of mass production-based competition (Goldman *et al.* 1995).

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Agile manufacturing is not simply concerned with being flexible and responsive to current demands, though that is an obvious requirement. It also requires an *adaptive capability* to be able to respond to future changes. This has two elements: (i) development of internal capability. For example, a lead-time reduction target may be achieved through product redesign, using JIT or the improvement of an MRP system, leading to capabilities in design, factory-floor organization; (ii) ability to configure the company's assets (human and capital) to take advantage of future short-lived opportunities. This may depend on the use of technology, flexible organization, or the reliance on shifting alliances, created and dissolved according to market needs. Agile and lean are not synonymous. One of the biggest differences between the two can be seen in supplier relationships. Lean manufacturers, particularly Japanese auto makers, believe that successful manufacturers can find the best suppliers by searching the market of open competition (border-crossing) whenever they need a service (Booth 1996).

The concept of agile manufacturing was propounded in 1991 at the end of a government-sponsored research effort at Lehigh University. In the business world, to be 'agile' is to master change and uncertainty, and to integrate the business' employees and information tools in all aspects of production (Anonymous 1995). For the customer, agility translates into customer enrichment. The goal of an agile manufacturer is to present a solution to its customer's needs—and not just a product. A producer does this by learning what a consumer needs now and will need in the future. For businesses, agility translates into co-operation that enhances competitiveness. An agile partnership crosses company borders and works together. A company that can best perform a particular business function shares that knowledge with other companies in the industry. Critical to successfully accomplishing agile manufacturing are a few enabling technologies, e.g. the standard for the exchange of product model data (STEP), concurrent engineering, virtual manufacturing architecture, component-based hierarchical shop floor control system, information and communication infrastructure, and organizational and behavioural changes (Cho *et al.* 1996).

There is a number of research reports available in the literature that discuss the concept of agile manufacturing (for example, Youssef 1992, Burgess 1994, Noaker 1994, Pandiarajan and Patun 1994, Goldman *et al.* 1995, Cho *et al.* 1996, Murray 1996, Spencer 1996). However, there is little or no effort made to present: (i) a comprehensive analysis of agile manufacturing concepts, both from a strategic perspective and enablers points of view in order to motivate the researchers and practitioners in agile manufacturing research and applications; and (ii) a framework for the development of the agile manufacturing system.

Realizing the importance of agility and the role of information technology in manufacturing, an attempt has been made in this paper to review the concepts and enablers of agile manufacturing, whilst developing a framework for the development of agile manufacturing systems (AMS) and to suggest some future research directions.

2. Agile manufacturing

Agility in action represents a paradox, because firms compete and co-operate simultaneously. Agility, as the conventional meaning, denotes a fast-moving, agile actor. As described by the proponents of the agility concept, agile corporations are able to rapidly re-organize and even reconfigure themselves in order to capitalize on immediate, and perhaps only temporary, market opportunities. It is readily acknowledged, however, that no one firm will have all the necessary resources to meet every such opportunity. Core competencies of organizations can be pooled to reduce the time to market. Virtual corporations, enterprise re-engineering and adaptive/agile manufacturing are all new concepts based on the accomplishments of integrated manufacturing of the past decade. The new manufacturing enterprises are characterized by an ability to effect flexible reconfiguration of resources, shorter cycle times and quick responses to customer demands. Information is a key factor in transcending physical barriers and imparting the enterprise-oriented agility and adaptiveness to organizations (Pant *et al.* 1994).

The following are system's focus from the view of agile manufacturing concept: product and process R&D sourcing/partnering strategy; prototyping; customer support; supplier/customer/partner relations; and logistics. The agile manufacturers should respond to: (a) rapidly changing markets; (b) global competitive pressures; (c) decreasing new product time-to-market; (d) increasing inter-enterprise co-operation; (e) interactive value-chain relationships; (f) global sourcing/marketing/distribution; and (g) increasing value of information/service, and in all areas of manufacturing enterprise. Agile manufacturing proposes to create an open, scalable infrastructure for manufacturing, and to demonstrate its effectiveness in pilot production. The infrastructure should provide standardized ways of assessing a wide variety of agile production services over local area networks (LAN), as well as the Internet. The infrastructure is open because anyone will be able to offer services; it is scalable because no distinction is drawn between services available on one's own shop floor, those obtained from other parts of one's company, and those obtained from other companies across the country. A fully developed agile manufacturing system will provide access to a national network of agile manufacturing services that a company can utilize as seamless extensions of their own internal production capabilities.

The difference between traditional and current practice in manufacturing is presented (table 1) with the objective to demonstrate the potential of agile manufacturing. It can be seen that the traditional practices rely more on a standardized product, a longer market life for products which are produced to forecast with low information content. The current focus of manufacturing is on customized products, open ended-platform, shorter market life, high information content and long-term relationship with customers. All these current expectations regarding product and production can be met by agile manufacturing practices, e.g. quick response manu-

Traditional practice	Current focus
Uniform/standardized	Highly variable/customized
Self-contained	Open-ended platform for upgrades/ information/services
Expected to have a longer market life	Expected to have a shorter market life
Produced to forecast	Produced to order
Low on information content	High information content
Priced by manufacturing unit cost + margin	Priced by customer perceived value
Characterized by a specific-market niche	Characterized by multiple-market niche

Table 1. Traditional versus current focus on manufacturing.

Areas in manufacturing	Strategies for agile manufacturing
Marketing	Individual customer-perceived value
Design and production	Rapidly producing variety of goods and services to customer order in arbitrary order quantities, a methodology that integrates supplier relations, production processes, business processes, customer relations, and the product's use and eventual disposal
Organization	Ability to synthesize new productive capabilities—facilities and skills regardless of their physical location
Management	Leadership, motivation, support and trust
People	Knowledgeable, skilled, empowered and entrepreneurial total workforce

Table 2. Multi-facet of the agility in manufacturing.

facturing and rapid prototyping. An agile system will supersede mass production for a high-value-added end of the market with the help of advanced computers and communications (Preiss 1994). The multi-facet of the agile manufacturing is presented in table 2.

In the following section, enablers of agile manufacturing are discussed in detail taking into account the current focus in manufacturing.

3. Enablers of agile manufacturing

Researchers have approached the management of agile manufacturing from a variety of perspectives, using a wide range of tools. The purpose of this paper is to bring them together for the design and implementation of agile manufacturing systems (AMS). The following enablers of agile manufacturing are discussed in this section: (i) virtual enterprise (VE) formation tools/metrics; (ii) physically distributed teams and manufacturing; (iii) rapid partnership formation tools/metrics; (iv) Concurrent Engineering (CE); (v) integrated product/production/business information system; (vi) rapid prototyping tools; and (vii) Electronic Commerce (EC).

A conceptual model has been developed, as shown in figure 1, to illustrate the enablers of agile manufacturing. In order to achieve agility in manufacturing, physically distributed firms need to be integrated and managed effectively so that the system is able to adapt to changing market conditions. It can be seen from the conceptual model that different enablers of agile manufacturing are overlapping each other. Therefore, all the enablers/tools should be integrated to achieve an effective integration and management of firms in a virtual enterprise.

Further details on the enablers of the agile manufacturing system are presented in the following sections.

3.1. *Virtual enterprise formation tools/metrics*

Virtual enterprise facilitates the reconfiguration of the organization in order to respond quickly to changing market needs. A single organization is often not able to develop sufficient internal capabilities to respond effectively within a short period of time. In a virtual enterprise, one organizational entity may take on the responsibility for design, while another performs manufacturing. That is, each functional aspect of the manufacturing design, production and marketing of a product may be performed

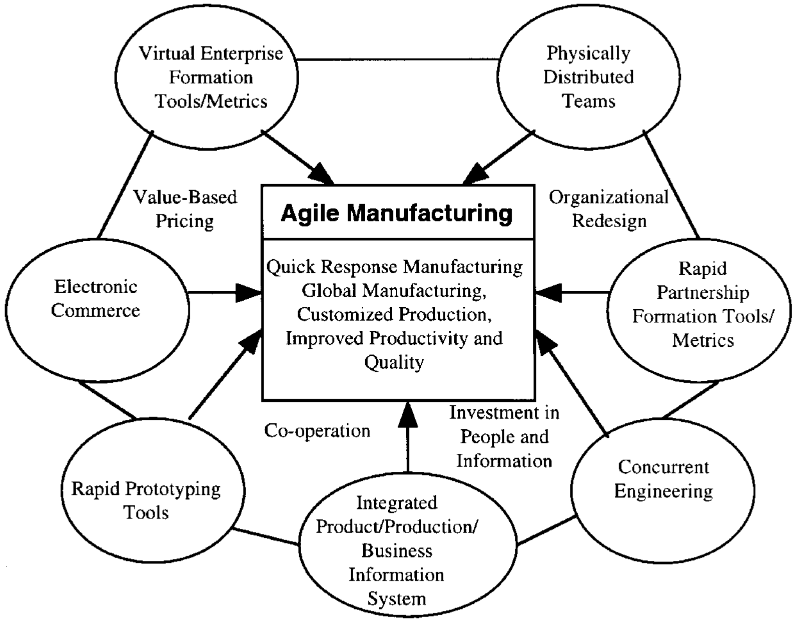

Figure 1. A conceptual model to illustrate the concept and enablers of agile manufacturing.

by many different organizations. Co-ordination and integration are especially complicated under such an arrangement. Successful attainment of the business goals of the virtual enterprise therefore depends on its ability to align the business processes and practices of partner firms. Moreover, a virtual enterprise can define and re-engineer its business processes to achieve a competitive position (Rolstadas 1995).

The virtual enterprise environment places a number of special requirements on the process design activity. By definition, virtual or distributed enterprises are temporary. This mandates that such organizations must be easily assembled and disassembled. Individual partner organizations do not cease to exist during their membership in the virtual enterprise. This point highlights another important issue, security. These require appropriate industrial legislation and legal protection to be established. Partner-organizations may remain competitive in some markets or return to a competitive relationship with other partners after the dissolution of the virtual enterprise. Sensitive information and business processes must be protected as part of the overall business process design, so as to enable the type of communication necessary to allow the partners to perform successfully as a single entity. Computerized information systems with suitable protection may help to safeguard sensitive information.

Agile manufacturing requires the development of a system that embraces virtual design, virtual manufacturing and virtual assembly. This system should be aimed at extending the capabilities of existing parametric CAD/CAM systems, which can be linked to a system such as Pro/Engineer or Master Series. The system interface with the CAD system through a data integrator will provide a two-directional flow of data among them (Parks *et al.* 1994).

An Internet-assisted manufacturing system would be appropriate for agile manufacturing practice (Wang *et al.* 1996). It may consist of a CAD/CAPP/CAM/CAA integrated Central Network Server (CNS) which links to local FMS or CNC machines by means of cable connections. After a local user inputs the product information, the CNS can generate complete CAD/CAPP/CAM/CAA files and control the remote FMS or CNC machines to accomplish the whole production process. This system uses the Internet as an interface between a user and the CNS, and allows a local user to operate 'remote' machines connected to the Internet. Wang *et al.* (1996) also proposed to build a network of manufacturing databases and a research database to improve manufacturing agility. The following are some of the performance measures that can be used to evaluate the effectiveness of the formation of the virtual enterprise: time to identify the core competencies of partner-firms; new product development time; technology levels; innovation; flexibility; delivery performance; quality; inventory; virtual enterprise development time; profitability; and IT skills and knowledge using these metrics.

3.2. *Physically distributed teams and manufacturing*

New types of logical infrastructures, e.g. physically distributed teams and manufacturing support agility and quick responses with the objective to reduce the time to reach the global market. For example, nowadays, companies rely on internal shops or fewer familiar contractors for prototyping and the JIT production system. Establishing relations with new suppliers can take months, because everything from terms and conditions to CAD formats must be negotiated, and the supplier's capabilities must be validated. The physically distributed enterprise is a temporary alliance of partner enterprises located all over the world, where each contributes their core competencies to take advantage of a specific business opportunity or fend off a market threat. These opportunities or threats are typically short term and arise suddenly in the competitive environment (Vastag *et al.* 1994). Moreover, innovative research in distributed artificial intelligence and intelligent manufacturing systems is essential for physically distributed manufacturing organizations. These will help to integrate the system across the heterogeneity barriers created by the system's components. This integration will satisfy new requirements for integrability, configurability, adaptability, extendibility and reliability, and ultimately agility.

Electronic mail systems and networks enhance the possibilities of distributed manufacturing environment, and hence distributed teams. Communication via electronic networks with some sophisticated features will improve the co-operative supported work in a distributed team and manufacturing environments. For example, a graphical user interface may allow front-end to the Internet. Also, using Multimedia, video conferencing can be organized to educate and train the people on a particular technology or method. The manufacturing shop-floor experience demands operational and organizational flexibility and adaptability to meet changes in markets and technology. In addition, other demands are being placed for quicker and less expensive system installation and start-up to assure survival of the enterprise. Therefore, the document structure, milestones and preparation should be addressed with the objective to improve the collaborative supported work in such a manufacturing environment.

3.3. *Rapid partnership formation tools/metrics*

In a distributed global manufacturing environment, there is a need to develop co-operative supported work by forming suitable partnerships or teams. This could be achieved through the alignment of business, manufacturing and operational strategies, and the development of a management control system using advanced information technology and new management concepts. Partnership formation in a VE provides firms with new technologies and products, critical resources, new markets and core competencies. Furthermore, the evaluation of firms for partnerships should include both strategic and operational factors. Partnership formation precedes the virtual enterprise formation. VE formation involves the integration of partner-firms with the help of various information technologies, organizational restructuring, and training and educating employees in the new environment. Partnership formation requires the analysis of strategic and operational opportunities of potential partnering firms. It involves aligning strategies and pooling of core competencies based on the competitive strategies of the firm. The partnership formation is a sub-function of VE formation. However, techniques/tools used in both these cases can have common characteristics. The purpose of focusing on the partnership formation is to highlight its major role in agile manufacturing.

In an agile manufacturing environment, strategic partnerships play an important role in responding to markets as quickly as possible. In a virtual enterprise, the coordination and integration of partnership firms' activities are essential for the successful business performance. Criteria, e.g. consistency of culture, market intelligence, number of distribution channels, new technologies, product development time and costs, flexibility, inventory turnover, R&D costs, and market share for new products should all be considered in the partnership formation. The life cycle of the product is also to be considered while choosing criteria for partnership formation in a VE.

Improving the responsiveness of a firm to a changing market requires a shared partnership between the core parts of the firm. Shared understanding of marketing and manufacturing's approach is the starting point. The other is building on a shared understanding of the market itself to move to a customer-driven knowledge enterprise (Berry *et al.* 1995). The main objective of the partnership program is to position a company in the competitive global manufacturing spectrum by combining its technical sales and marketing skills with those of the leader in manufacturing enterprises. Since the time to market products should be reduced, the selection of partners should not take longer, so that the overall time to market products can be reduced. This could be done with the help of information technology, trade associations and partner-rating. The criteria for partnership formation should be based on delivery performance, product quality, infrastructure, productivity and the level of IT skills to ensure an effective strategic partner in a virtual enterprise. The competitive advantage that can be achieved by a VE depends on how well the individual firms complement each other and their ability to integrate with one another with their core competencies (Meade *et al.* 1997).

Since the market is turbulent and uncertain, a firm should respond as quickly as possible to capture the market. This could be achieved by rapid partnership formation tools, e.g. information technology that includes Multimedia, Internet, database, Microsoft Project, Case Tools and Electronic Data Interchange, and metrics, e.g. QFD for selecting partner firms, benchmarking, review of past performance and their core competencies. Also, a set of metrics based on both financial (e.g. rate of return on investment, sales revenue, profit, increase in market share) and non-financial (time to develop new products, time to reach new market, manufacturing cycle time, time to complete the partnership formation process) performance measures can be used to evaluate the performance of partnerships and partnership formation processes in an agile enterprise.

3.4. *Concurrent engineering*

In an agile environment, there is a need for a quick responsive manufacturing system. Concurrent engineering is the answer to the need for shorter product development cycles and hence to respond as quickly as possible to changing markets. The application of CE in product development indicates that new products are designed with inputs from all concerned. First and foremost is the customer, who will determine the ultimate success of the product. If the target requirements are well defined and documented, then the product specifications can be focused on customer needs. The methods of quality function deployment (QFD) are designed to listen to the voice of the customer, especially for evolutionary products, where the customer is well aware of the current choices and capabilities of available products. Also, CE is very much part of other enablers in an agile manufacturing environment.

The integration and coordination of partner-organizations' business processes and practices can be viewed as a natural extension of concurrent engineering methods (Vastag *et al*. 1994). Also, the issue is the requirement to provide a common basis for communication between partner-organizations. In a virtual enterprise, there are no pre-existing semantic norms or communications channels. Disparate semantics and procedures must be coordinated towards a single goal within the interdisciplinary CE team. In the CE environment, other interested departments, e.g. field service, quality, marketing and manufacturing, contribute strongly to new product design and specifications to assure good warranty levels, easy serviceability and testability of the product. The strategy of the CE effort is to combine the connectivity of CAE/CAD/CIM with the design for manufacturing, and to get manufacturing involved early in the design of the product. This helps us to eliminate many non-value-adding activities at downstream activities, e.g. engineering, production, distribution, accounting and customer service. By eliminating non-value-adding activities, the system should be able to respond to changes in the market requirements. Nevertheless, CE can be applied in almost all areas of VE to facilitate agility.

There are also several tools and techniques which assist design and manufacturing engineers to improve the product development process in a CE environment. Some of these include: functional analysis; CAM tools; NC verification; solid modelling; finite element analysis; optimization; design for cost; value engineering; design for manufacture; design for assembly; design for ergonomics; design for reliability; Failure Mode and Effect Analysis (FMEA); robust engineering; and Taguchi methods (Hills 1992). In a virtual/distributed manufacturing environment, the information systems can be integrated using CE and system modelling using Object-Oriented Programming (OOP) with the objective to eliminate non-value-adding activities either at the design of virtual/distributed manufacturing systems stage or at the product design stage. The application of CE is inevitable to respond to uncertain and turbulent global multiple-niche markets. In addition, the CE can be applied in the selection of partnership, rapid prototyping, rapid partnership formation, organizational restructuring and process reengineering in a virtual enterprise.

3.5. *Integrated product/production/business information system*

To achieve configurability economically in an agile manufacturing environment, a consistent software representation of manufacturing entities is required. It is necessary to avoid generic control functions from the wide variations found in low-level devices. System information must be organized in a standard format allowing other entities to understand and use the information effectively. For effective production control in an agile manufacturing environment, manufacturing information systems must access a number of data sources, including independent computer packages, proprietary database systems and test equipment. In a virtual enterprise, the integrated information system becomes complex because of the physically dispersed partners. Each partner may have their own control system for their operations and they should be linked with other partner firms. Also, because of the language and differences in the system and skills available, there is a need to establish a communication network for exchange of information on various production/operations, achieved through advanced information technologies, e.g. Multimedia, Internet and EDI. Most existing systems are disjointed, or only partially integrated, leading to a number of problems with data access, format, translation and transfer. The solution to such problems involves either rebuilding the entire information system from scratch, which is costly and disruptive, or the adoption of an integration strategy to build a more cohesive system. The information technology should support the following functional objectives in an agile environment (Choi *et al.* 1996, Duffie and Prabhu 1996):

(i) Openness—reliance on published and widely implemented interface protocols, so that anyone can use and offer services through agile infrastructure for manufacturing systems, including services that enhance the structure itself.
(ii) Scalability—the ability to access services across the shop floor or around the world using the same protocols.
(iii) Extendibility and graceful degradation—services can be added, removed or substituted at any time, with incremental changes in performance.
(iv) Compatibility—with legacy systems through encapsulation.

3.6. *Rapid prototyping tools*

Prototyping describes the design and generation of an early version of a product. The version does not necessarily have all the features of the final product, but has enough of the key features to allow testing of certain aspects (e.g. visual, physical, functional) of the product design against the product requirements. Rapid prototyping with help of advanced computer technologies, e.g. CAD/CAE and CE, helps to reduce the time to develop a product and reduce the non-value-added activities at the design stage itself. This helps to improve the responsiveness of the overall system for customer requirements. Therefore, rapid-prototyping is one of the major enablers for agile manufacturing.

Virtual Prototyping (VP) is the design and generation of an early version of a part in a computer-based (i.e. 'virtual') environment. The term 'virtual' implies that the product design is not yet physically created, but a computer-based representation of the product is presented to the user for observation, analysis and manipulation. The cost involved in generating a virtual prototype is generally less than the cost of building a physical prototype. Hence, a virtual prototype can be a valuable alternative to an otherwise expensive physical prototype. Furthermore, the short time cycle from design to manufacture to testing in VP ensures that the designer can be promptly informed of any design errors. The main steps involved in VP are Design, Manufacturability Analysis and Re-design. The design of a part is typically achieved by solid modellers. These tools help to improve the agility in manufacturing (Spreng *et al.* 1996).

3.7. *Electronic commerce*

Electronic commerce means using technological advances to promote everything that is commerce. EDI is set to become the standard by which organizations will communicate with each other in the world of electronic commerce. As a cost-conscious, highly competitive electronic commerce environment comes of age, businesses are looking at electronic data interchange (EDI) in a new light. EDI is defined as the communication of business information between computer applications in a standardized electronic form. In short, EDI communicates information pertinent for business transactions between the computer systems of companies, government organizations, small businesses and banks. Its use is growing and it is set to become the standard by which organizations will communicate formally with each other. Nowadays, computers simplify and enhance communication between global trading partners, and enable new business practices like global procurement and sourcing.

Since a close interaction between customers and supplier is essential for the agile manufacturing, the electronic commerce inevitably takes into account the geographically dispersed customers and their requirements. Clearly, companies and consumers are discovering that global networking and other technological innovations are powerful assets if used as competitive weapons in their day-to-day activities. These activities range from being entertained and educated by material on the USENET and World Wide Web to building a business serving customers on the Internet. These activities also permeate organizations where increased demands for the efficient collection, dissemination and processing of information are evident because of various economic factors—global competition and other market forces—and consumer demands for high service and improved quality. These demands are forcing agile companies to integrate previously isolated 'islands of automation' into coherent weapons.

The main motivation behind electronic commerce is to improve the response time to customer's demand as quickly as possible by directly collecting the customer's requirements through an on-line communication system, e.g. Internet and www. This will help to reduce the time to reach the market and will be flexible enough to interact with customers for mutual agreements, and add some human touch to the order by closely interacting with customers. Agile manufacturing organizations can essentially see EDI as a tool for reducing cycle and order fulfilment times. The primary benefit of EDI to businesses is a considerable reduction in transaction costs by improving the speed and efficiency of filling orders. In addition, the common communication channel between trading partners can foster closer relationships. All this can result in important competitive and strategic advantages.

4. A framework for the design and implementation of agile manufacturing systems

In this section, a framework will be discussed for the design and implementation of agile manufacturing systems (AMS) with the help of a conceptual model, as

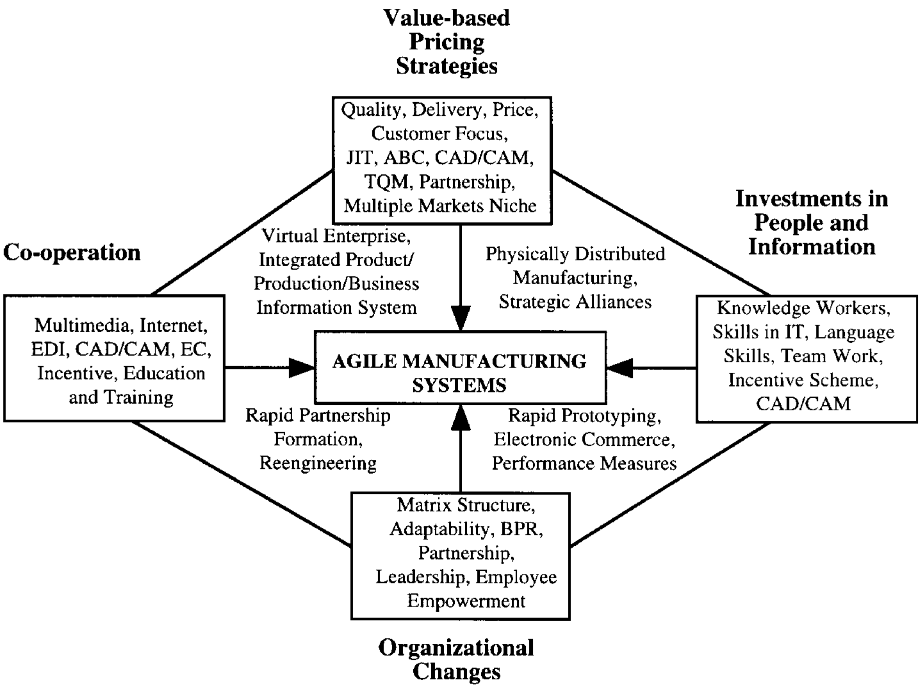

Figure 2. A framework for the development of agile manufacturing systems.

shown in figure 2. The conceptual model illustrates the major strategies/techniques of the agile manufacturing. These strategies are integrated with appropriate enablers of agile manufacturing to develop an adaptable organization. The manufacturing practice for managing agility should include enterprise integration, shared databases, multimedia information networks, product and process modelling, intelligent process control, virtual factory, design automation, super-computing, product data standards, paperless transactions through electronic information interchange and high-speed information highway. Each partner in a Virtual Enterprise (VE) concentrates on improving their own agility to reduce the manufacturing cycle time, and hence to improve the level of overall flexibility and responsiveness of the organization. The model indicates that there is a need to integrate all the partnering firms to improve the effectiveness of the whole organization. The agility of each partner-firm is influenced by other partnering organizations. Therefore, there is a need to improve the agility in an integrated framework. The level of agility can greatly be increased by properly aligning the business and manufacturing strategies of all the partner-organizations in a physically distributed manufacturing environment.

4.1. *Agile enterprise design strategies*

The development of a framework for agile manufacturing systems involves looking at the broad-based strategies with the objective to determine the implementation details of agile manufacturing. For example, the ability to produce goods and services to order can be achieved by implementing just-in-time and flexible manufacturing. JIT may be suitable for make-to-order and facilitate quick response manufacturing and hence agility. However, the organization as a whole should be reconfigurable in order to make use of short-lived opportunities. For this, the agile organization should have the infrastructure based on physically distributed manufacturing and teams using advanced information technology. Similarly, the ability to produce goods and services to order can be achieved by rapid-protyping facilities. The appropriate manufacturing strategy for shorter product life-cycles should be based on the product life-cycle stage. The concept of re-engineering can be used for restructuring the organization based on its core business processes and competencies.

4.1.1. *Value-Based Pricing Strategies (VBPS)*

These will set the agenda and justify the need for agile manufacturing to enhance the competitive position of the company. Also, value-based pricing strategies, e.g. quality, deliverability and cost, will demand manufacturing methods and technologies, e.g. JIT, MRP, FMS, ABC and ABM to facilitate the agility of the organization. Companies need to have an information system in place so that data on the needs of customers and the market as a whole can be collected and analysed with the objective to identify the level of price, quality and delivery performance that add value to the customers. As noted earlier, advanced IT can be used in collecting and analysing data about the markets and their demands. The VBPS may lead the companies to select suitable partner-organizations, invest in education and training programs, and organizational changes to support the formation of a virtual enterprise. For example, VBPS may select 'cost reduction' as the strategic option for improving productivity and quality by eliminating non-value-adding activities in all partner-firms of a virtual manufacturing enterprise. The 'cost reduction' strategy can select the re-engineering or cellular manufacturing as the manufacturing strategic option. This particular strategic option needs to be promoted among all partner-organizations. Many other associated strategies/techniques for rapid-partnership formation and rapid prototyping can be employed to reduce the lead time of delivering products and improve quality, thus increasing the value to the customers on their investments. For example, business process redesign can be used for non-value-adding processes/products from a business and hence provide sufficient strategic information on partnership formation in agile manufacturing.

4.1.2. *Co-operation*

The co-operation between partner-firms within a physically distributed/virtual manufacturing enterprise is important to improve the responsiveness of the whole organization to the customer's demand and be competitive in terms of offering quality goods and services, and price. The collaboration between partner-firms in a virtual manufacturing enterprise can be achieved by an effective communication system that includes training and education on advanced IT, e.g. Multimedia, Internet, EDI, CAD/CAM, Case Tools and Electronic Commerce. In a distributed manufacturing environment, the co-operative supported work is difficult to obtain because of the varying characteristics of partnering firms. However, an open communication system using advanced information technology, e.g. Internet, WWW and Groupware, will facilitate a high-level of co-operative supported work. Suitable incentive schemes are to be established to encourage co-operation among partner-organizations in a physically distributed manufacturing environment. Also, supply chain re-engineering can be adopted as a strategy to improve the co-operation among various physically distributed firms in a VE. For example, re-engineering a business process requires the elimination of non-value-adding activities by improving the information flow and hence the co-operation among partner-firms.

A firm should first formulate business strategy based on the nature of the market, and the nature of products and services to be delivered. Then the firm can look into the characteristics of potential partner-organizations, e.g. infrastructure, strategies, production control system and cycle time. It has to assess the level of the team working by studying the information system, and hence the communication between partner-organizations, to obtain the best co-operation for creating value to the customers by reducing the cost of production. For this purpose, the company has to maintain a database or access online information available on the profile of potential partnering firms. Based on a set of criteria, e.g. productivity, quality, dependability and flexibility, the partnership should be formed to achieve a high level of co-operation. Also, the lead firm should take into account the organizational structure when deciding about the team and co-operative supported activities between partner-organizations in a virtual organization. For instance, the lead firm has a matrix organizational structure which is different from a partner-firm. In this case, it is difficult to obtain the co-operative work at different levels, e.g. strategic, tactical and operational, because of the nature of the decision-making characteristics. The 'co-operation assurance' system of each firm should be evaluated based on a set of criteria, e.g. the capital and skills available in the company, and the experiences of the company in the past with other virtual companies and their overall performance. Since firms are either distributed locally or globally, there is a need to consider each firm's organizational structure and employees' culture in determining the partnership for a VE. Also, standards are to be established both for the information exchange, software and hardware, and goods exchanged between partner-firms to resolve any communication and delay problems.

4.1.3. *Organizational changes*

The organizational structure in agile manufacturing should encourage team work and integration of partner-organizations in a physically distributed manufacturing environment within a short-period by: (i) handling high information technology content; (ii) knowledgeable workers with adequate skills in computers; and (iii) flexibility that is enough to reconfigure itself whenever the market opportunity shifts over time. Operational characteristics of the entities in a distributed autonomous shop-floor are a loosely arranged federation of co-operating agents with capabilities for scheduling in relative isolation. The organizational changes are to be based on matrix organizational structure, and require training and education, employee empowerment and leadership to support agility in manufacturing organizations. Once a partner is selected based on market objectives and business strategies, then a suitable organization can be established with key members from each partner-firm of a virtual enterprise. The responsibilities and authorities of employees are to be clearly defined with co-operating firms in a physically distributed manufacturing enterprise. For this, the nature of the information flow and material flow have to be analysed, with the objective to develop an organizational structure, which in turn improves the overall responsiveness of the organization. Moreover, heterarchical or holonic control architecture for distributed manufacturing systems and flexible communication channel will improve the agility of the enterprise. The partner-organizations can be networked to have autonomous strategic business units.

The nature and level of employee empowerment in such a virtual organization are to be defined to enhance the agility, and hence to support the overall business objectives of the organization. For example, managerial employees can have an authority on the changes to be made to the design of products and forward the suggestions to the lead firm. The purpose of the design of agile organization is not only supporting the virtual enterprise, but also to improve the effectiveness of communication systems, and hence eliminating any kind of non-value-adding activities.

4.1.4. *Investments in people and information*

Since physically distributed virtual manufacturing is knowledge based and information intensive, there is a need to obtain co-operative supported work from geographically dispersed employees who may have different backgrounds, business strategies and objectives. Because of the information-intensive nature of the tasks, there is a need to invest in training and educating people in information technology, modelling techniques and concepts, e.g. object-oriented programming, CAD/CAE, MRPII, JIT, Internet and WWW. Suitable incentive schemes are to be established to encourage people to work as a team in a distributed manufacturing environment. Also, standards are to be set for the type of education and training of employees to work in a virtual manufacturing enterprise. TQM can be in-built as part of the training and education of employees in an agile environment. There is a need to create a circle that consists of key members of each partner-organization so that co-operative work can be obtained to respond to the changes in markets in a short timespan. To encourage innovation about various enablers, and enterprise integration and management, suitable reward schemes may be helpful. For instance, a reward scheme based on both financial and non-financial measures, e.g. ROI, profit, revenue, flexibility, productivity, innovation and quality would be appropriate in such a complex and temporary multi-organizational set-up. Because of the holonic/heterogeneous nature of agile enterprise, there is a need for employee empowerment with the objective to support various business processes. This again requires special training to work in a virtual environment.

4.1.5. *Summary of strategic options*

A summary of the strategic options available to achieve agility in manufacturing is presented in table 3. For example, marketing function has to focus on customized production. Accordingly, the marketing function should give feedback on the customer requirements and trend in markets. The design-firm should quickly translate the customer requirements into design parameters using the concept of concurrent engineering, cost analysis and rapid prototyping tools. Similarly, production function should manufacture goods in a physically distributed environment as quickly as possible with the help of advanced IT and effective distributed teams. Since facilities and co-operating firms are located in different places, there is a need to have an organization for effectively managing the distributed partner-firms, and to support the flexibility and responsiveness of new production capabilities with the help of suitable education and training, and empowerment of employees. For example, matrix organization may facilitate a team working by smooth information flow in a physically distributed manufacturing environment.

Motivation of agile manufacturing	Manufacturing strategic options
Fragmentation of mass markets into multiple niche markets	Market research, R&D, VE formation, electronic commerce
Ability to produce goods and services to order	Just-in-time and flexible manufacturing
Ability to treat mass market customers individually	Rapid prototyping, rapid partnership formation
Shrinking product lifetimes	Life cycle manufacturing
Fusion of goods, information and services	Computer-integrated information systems
Emergence of global manufacturing systems	Supply chain management
Co-operation among companies	Network of firms
Distribution infrastructure	Logistics
Corporate reorganization	Business process re-engineering
Social values	Environmental issues

Table 3. Motivation of agile manufacturing versus manufacturing strategic options.

4.2. *Implementation details of agile manufacturing*

In an earlier section, we discussed the strategies for agile manufacturing and the role of enablers. In this section, an attempt has been made to present the implementation details of various enablers of agile manufacturing.

The agile manufacturing system requires interactive computer systems for customers to configure a design. This will bring the customer and the firm closer to each other to exchange information about product and service requirements, so that the firm can produce the right product at the right time and for the right market. Groupware, e.g. Microsoft Project, EDI, Case Tools, WWW and Internet enable people located remotely to work co-operatively. There is a need to maintain a common platform and standards in the communication systems so that different collaborating firms are effectively linked in the virtual enterprise. Furthermore, the integration between human and machines can be improved by a communication system using the Multimedia application to facilitate easy understanding of the company's goals and objectives, and in turn obtain a co-operative supported work. In order to reduce time to market products, the application of CE in the enterprise-wide activities of the partner-firms needs to be considered. The relationship between customers and the lead firm can be improved by electronic commerce using international networks, e.g. Internet and WWW. Open communication architectures may provide easy access to information related to market requirements and production-operations, which in turn facilitate rapid prototyping and integration of partner-firms in a virtual enterprise. Also, powerful tools, e.g. computer-simulation models, can be employed in the design, production planning, and object-oriented modelling and programming to develop an agile manufacturing system. In addition, the concept of 'design reuse' or 'feature-based design' can be used to reduce the time to develop new products, and hence to enhance the responsiveness of the organization.

4.2.1. *Virtual enterprise formation*

In an agile manufacturing system, a production service may itself be a virtual enterprise, relying on other network services to do its work. For example, corporate-level agents delegate jobs to the shop-floor agents that actually perform work; shop-floor agents, in turn, may delegate jobs to other workcells. These agents can use brokers to locate appropriate providers, or bid on jobs for themselves. They can also call on providers of manufacturing support services, e.g. scheduling and process planning.

The design and implementation of agile manufacturing require Virtual Manufacturing Entities (VME). A VME has been defined as an abstraction of a specific set of resources and functions possessed by a physical device. VMEs are a standardized representation of the real environment. They can be used as a loose coupling mechanism in constructing integrated control systems for agile manufacturing. Their design and implementation are guided by the physical structure of real manufacturing entities, simplifying these tasks for software developers, and bridging the gap between developers and users (Beaumariage *et al.* 1995). As noted earlier, the virtual enterprise is like a vehicle to achieve agility in manufacturing. Therefore, a virtual enterprise should be given due consideration in the implementation process of agile manufacturing.

Virtual manufacturing is to design products and control production operations with the help of computers. This will facilitate conducting experiments in off-line mode rather than on-line in a real life manufacturing environment to eliminate wastage and reduce time to reach markets. In virtual manufacturing, the machine modelling can be built within the CAD system through the customization of the CAD menu systems. This can be done with tools, e.g. Pro/Engineer or Master Series. Its goal is to provide a means of creating any machine found on a factory floor, e.g. mills and lathes in any partner-firms. Not only would the geometry be created, but also the functionality of the machine. The virtual design system is to aid in the conceptualization of three-dimensional parts. As parts are created with the implementation of CAD, they are seamlessly brought in the virtual design system for analysis. Parametric design changes can be made and sent back to the CAD system. All changes are reflected automatically in the design system. Most parts are designed to fit together with other parts. Full assemblies can be brought into the virtual assembly system and separated into the individual components. Each part can then be assembled through direct manipulation of the parts to form the final assembly. Issues, e.g. handling, ease of assembly and order of assembly can be studied. The virtual manufacturing system is designed to aid in the process planning stages of a part. As parts are designed and NC codes generated, the virtual manufacturing system would allow designers to test the NC codes on the actual machines of the plant, which were replicated using the machine modelling system. This way, machine limitations, fixture placement and NC codes can be tested without committing actual machine time or material costs. The user of the system would interact with the machines in as normal a manner as possible through the use of VR hardware.

A major problem in conventional and virtual manufacturing has been the lack of integrated tools for the off-line development and testing of cell control programs (Witzerman and Nof 1995). Control device programs are typically created and evaluated using stand-alone computer simulations or actual production hardware. In contrast, graphic simulation/emulation workstations can provide a virtual environment for robotic cell layout, device selection, path planning, programming and testing. The resulting off-line task programs may then be translated into native robot languages and downloaded to production hardware.

4.2.2. *Physically distributed teams and manufacturing*

In the case of physically distributed manufacturing, research centres, consortia and manufacturing companies can explore multi-agent systems for suitable solutions. Such multi-agent systems will require flexible control mechanisms for both creating and managing such agent communities. These virtual communities are supported by mediator agents which coordinate actions to satisfy local and global objectives. The physically distributed manufacturing system is thus populated by heterogeneous agents and structures of control, which operate autonomously during the planning and execution of the manufacturing tasks. To assist agile manufacturing in meeting the needs for integration, communication, collaboration and decision making, the concept of integrating MSS with a distributed group support system into a distributed manufacturing support system (DMSS) can be used (Gillenwater *et al*. 1995). From a global perspective and decision-making processes, information system requirements within the structural (organizational design) and infrastructural (information system design) elements of manufacturing need to be established. The result is a conceptual DMSS design that provides an intelligent interface, accommodates incremental manufacturing integration, offers controllable message exchange facilities, and allows configurable communication networks.

The use of heterarchical or holonic control architecture to control manufacturing systems is becoming increasingly attractive to conventional hierarchical architectures as the density and level of distribution of computing resources in manufacturing systems grow. Duffie and Prabhu (1996) reviewed design principles for hierarchical systems to reduce complexity, increase extendibility, self-configurability and adaptation in real time. The challenges that arise in adhering to these principles, e.g. co-operation between autonomous entities and potential for chaotic behaviour, are to be studied. Decision integration can be used to improve the quality of decision making in an agile environment. The problem of organizing decision-making agents into architectures of integration by analysing several elementary decision architectures for organizations, and comparing their optimal performance, can be used in the implementation of agile manufacturing (Papastavrou and Nof 1996).

The design of a distributed software architecture for an intelligent planning system based on a process model of cognitive systems (PMCS) was discussed by Flavell *et al*. (1996). PMCS is described in terms of its problem-solving behaviour and structure. For example, to bridge the gap between automation and robotic technologies, traditional automation hardware, e.g. parallel-jaw grippers and optical beam sensors can be combined with geometric planning and sensing algorithms. The resulting systems should be cost-effective, reliable and easy to set up and reconfigure, which in turn facilitates a planning process in an agile environment. In the PCMS, implementing a component of the functionality requires that autonomous knowledge sources co-operate by message-passing, in order to maintain a distributed model of the system's environment and synthesize decisions.

The modern modelling approach based on an object-oriented model is the suitable technique for modelling the agile environment, especially with fast changing reconfiguration of the organization concerning the changes in the markets. The reuse of the program for any changes in the organization's configuration and further experiments would be for the use of decision-making in the operation of physically distributed manufacturing. A formal object-oriented specification model (OSA), which is supported by a tool (IPOST) that automatically can be used to generate a prototype from an OSA model instance, allows the instance to generate a requirements specification (Jackson *et al.* 1995). Associated with the need to speak the same language at the human interaction level is the need for the systems infrastructures of partner organizations to communicate and co-operate to support the virtual enterprise in the agile environment. Data interchange and electronic communications protocol issues should be addressed as part of linking the information and production support systems of partner organizations. Additionally, the compressed time frame of the virtual enterprise requires the application of 'systems development methods' that will permit faster construction of the 'support systems infrastructure'. This type of reduction in the systems construction cycle type is only possible with methods that: (i) directly apply across design specification to the construction of support systems; and (ii) permit the reuse of components across system implementations.

4.2.3. *Rapid partnership formation tools/metrics*

Strategic alliances have become a popular competitive weapon in today's business environment and are applicable in agile manufacturing. The external factors to the network or supply chain, e.g. government policies, trade regulations and legislation, environmental aspects, inflation, overall economic situation in the country and competitors' actions will inevitably influence the agility. Therefore, there is a need to give due attention to these externalities of the network when making a decision regarding the nature of the partnership in manufacturing. All these externalities will act as constraints for the manufacturing system to function with a certain level of agility, which again depends upon the characteristics of other associated factors of agility. The use of reliable forecasting methods and market research will help to alleviate the problems of managing agility in manufacturing. Econometric models can be used, especially when dealing with external factors to the organization. The cost of capacity and various associated trade-offs should also be considered while formulating the policies for the management of agile manufacturing. Simulation methodology can well be used for studying the implications of agile manufacturing and the related cost behaviour. A matching pattern should be found with appropriate collaboration areas and levels in partnering firms.

The authority and responsibility for each partner-organization should be clearly defined in a virtual enterprise to achieve agility in manufacturing. Forming a suitable partnership is a time consuming process, in particular when geographically dispersed firms have different characteristics and the data to be analysed regarding the selection of partner-firms is enormous. This requires a system to process and analyse such data using advanced information technologies. It is essential to see that all the co-operating firms have adequate strategies and infrastructure that would meet changing market demands as soon as possible. There is a need to educate and retrain the employees to work as a team in a physically distributed enterprise.

The human relations management should be assessed with reference to agile enterprise, and the type of skills and co-operating environment for a physically distributed manufacturing organization. The reorganization of production in some firms, however, gives way to new social relations based on trust between the main actors: managers and union representatives. These firms are more characterized by open communication and mutual trust than by formal rules. These organizational innovations typically aim at both greater functional flexibility and workers support for the firm's production goals. These changes are made possible by the interaction of those present in the firm based on a consensus in decision making. The required co-operation is built on the reciprocity and mutual trust, not on coercion and external constraints. The transformation of the relationship is based on frequent face-to-face contacts. A new system of relations, initially not defined, is built by the representatives in a partnership where new forms of social relations are formed, linking the agents in a state of dependence, uncertainty and risk (Harrison and Laplante 1994). Tools, e.g. partner-rating using a questionnaire, QFD, are a set of criteria that are based on flexibility, production, quality and innovation. Therefore, the partnership between management of firms and labour union is essential for the successful development of an agile manufacturing system. Suitable contract/legal systems should be established with collaborating firms in the same line as construction projects. The effectiveness of the partnership formation process can be measured by the time taken to reach market, production lead time, overheads, market share, rate of Return on Investment (ROI), etc.

4.2.4. *Concurrent engineering*

The role of CE as one of the enablers of agile manufacturing has been discussed in § 3. Some of the implementation details on the application of CE in agile manufacturing are presented here. As mentioned earlier, CE plays a significant role in the design and operations of agile manufacturing enterprise, and in almost all the rest of enablers of agile manufacturing, e.g. virtual enterprise formation, rapid-partnership formation, rapid-prototyping and integrated product/production/business information systems. For example, there are tools available such as QFD for the implementation of CE in virtual enterprise formation and rapid-partnership formation. Similarly, CE can be used in the partnership formation process. For example, the characteristics of partner-firms and the product requirements can be matched using QFD, taking into account all the downstream non-value-adding activities. The implementation of CE in agile manufacturing can include: the involvement of a manufacturing process as early as possible; increase in cost awareness; recruitment of key players; the offer of training to key employees; the exploitation of CAD's power and application of analytical tools (Garrett 1990).

While recognizing the many benefits of CE, it is equally important to note certain constraints that will influence the process of its implementation. Some of these major constraints, as highlighted by Hills (1992), are: (i) incomplete requirements—due to external sources in the form of performance requirements mismatch and incomplete interface definition, as well as internal sources in the form of skill inadequacies; (ii) possible risk sources, e.g. (a) design team skill deficiencies, (b) different projects competing for the same resource and/or non-availability of tools or facilities when required, (c) effectiveness of funding profile, constraints and contract security, (d) financial and/or present economic environment, and (e) procurement due to delivery lead time default.

4.2.5. *Integrated product/production/business information system*

An integration strategy which uses an open system approach to recover data from the existing manufacturing system components and transfer the data into a common format can be adopted in agile manufacturing. Agile manufacturing systems can be conceptualized as having levels of strategy planning and traceability at each manufacturing system level. The traceabilities approach may provide a structured and holistic way of thinking about the physical system or narrower requirements of a computer management system. Harhalakis *et al.* (1994) focus on the development of a methodology within a software environment for automating the rule-based implementation of specifications of integrated manufacturing information systems. The specifications are initially formulated in natural language and subsequently represented in terms of a graphical representation by the system designer. A new graphical representation tool is based on Updated Petri Nets (UPN) which they have developed as a specialized version of Colored Petri Nets (CPN). The application presented here deals with the control and management of information flow between Computer-Aided Design, Process Planning, Manufacturing Resource Planning and Shop Floor Control Databases. This concept can be used to develop an integrated information framework for agile manufacturing systems.

Agile manufacturing systems require an IT system with the openness, scalability, extendibility and compatibility requirements by using the Internet to access agile production services. The top level architecture of AMS should be a loosely coupled collection of client and server agents. The servers encapsulate manufacturing resources and applications, and make them available as network services. The client agents make these services easy to use. Some servers play the role of intermediaries, providing directory, brokering, advertising, query processing and similar services. The agents communicate via structured messages that are readable by people and computers; messages are sent using ordinary Internet e-mail and other TCP/IP transport services. An agent-based architecture can be selected for an agile environment because (i) it is scalable simply by plugging in new services and intermediaries, and (ii) it gives each participating organization the flexibility to run whatever internal systems they wish, yet still interoperating with other members of the AMS consortium.

Object-oriented programming is now widely used in manufacturing application software development. OOP has advantages connected with handling complexity, reusability, extendibility, modularity and data abstraction, enabling it to handle modern programming requirements more effectively than conventional programming methods. Since agile manufacturing systems demand increasing complexity, flexibility and integration between computer applications, an object-oriented approach is particularly promising for the design and development of agile manufacturing information systems. Zhou *et al.* (1994) outline the concept of object-oriented methods and describe an object-oriented application development methodology for agile manufacturing information systems. They also presented a CASE (Computer-Aided Software Engineering) tool that can be used for system modelling and a direct source-code management information system, and a case study describing the development of a quality management information system which was implemented using a C++ development environment. Also, Kim *et al.* (1993) proposed a new information modelling methodology for manufacturing information systems called OOMIS (Object-Oriented Modelling Methodology for Manufacturing Information Systems). It consists of an analysis phase and design phase. In the analysis phase, manufacturing functions can be decomposed into component functions to define the information flow among the manufacturing functions and their infrastructures. The agile manufacturing functions should be described with functional diagrams. Then, functional diagrams are transformed into three types of tables: function, data and operation tables. In the design phase, these tables will be translated into object-oriented information relationship diagrams. Through an aggregation and integration process, these tables will be transformed into a class dictionary which consists of function classes and entity classes.

4.2.6. *Rapid prototyping tools*

Agile manufacturing enterprise requires the development of producible product configurations as proof of feasibility of design and manufacturing process validation. The stereolithography method can be used to produce three-dimensional parts from a CAD sold model without the use of tooling, cutting, numerical control or moulding. The process uses a computer-controlled laser beam to draw cross-sections of an object on the surface of a vat of liquid plastic. This is an excellent method for proving part design before production. Wright (1995) discussed the general principles of CIM in the context of specific technologies that create flexible factory systems, rapid part realization and in-process quality assurance. Manufacturing languages, common data structures, compatible operating systems, and common bus structures for machine tools and other processing agents in the factory are the key elements. The ability to rapidly convert design ideas to precision mechanical parts is presented by the author as a rapid prototyping case study that highlights the various principles involved in open-architecture and computer-integrated manufacturing. Spreng *et al.* (1996) presented the experiences of the car manufacturer BMW to explore a number of approaches to the problems surrounding the prototyping of mechatronic systems. Different CASE tools can be used to model both the digital (embedded controller) and analogue ('real world') aspects of the agile system design.

In agile manufacturing systems, there is a need for fast concept-to-prototype service as well as concept-cash, using the latest CAD and rapid prototyping technologies. Starting at any stage of the design process, the system should produce finished prototypes for engineering and market evaluation. Having prototypes in hand allows verification of a product, and ensures that faulty or difficult-to-manufacture designs do not end up in the final production. Rapid prototyping involves a software program that slices a three-dimensional CAD model into thin cross-sections or layers. A laser beam traces each layer onto the surface of a vat of liquid photopolymeric material which solidifies when exposed to ultraviolet light. The solidified layer is then lowered into the vat so that another layer of liquid is ready to be exposed to the laser. This process is repeated until all the cross-sections have been built up into a solid replica of the original CAD model. The resulting parts are strong enough to be snapped together, drilled and taped, finished and painted, and built into assemblies. They can also be used as mold patterns for casting parts in a variety of materials. Thus, rapid prototyping enables quick product development cycles which are essential for agile companies to compete in today's marketplace.

Shorter design cycles can be achieved by carefully managing the design process during rapid prototyping (Baldwin and Chung 1995). Traditionally, designers have used whatever tools were convenient at the time. This practice has resulted in steps being skipped and designs not being checked for important criteria until it is too late to make changes. These problems can be avoided through design methodology management, which ensures the appropriate sequence. Baldwin and Chung (1995) propose a maintainable, flexible methodology management system that supports the parallel execution of methodologies. Although initially developed for digital hardware synthesis, this system can also be applied to such domains as software development. The prototype is based on process flow graphs and design process grammars. The graphs describe the information flow of a design process, while the grammars transform high-level process flow graphs into progressively more detailed ones. The designer interacts with a Unix program called Cockpit, which tracks process flow graphs and informs the designers of possible actions. Process flow graphs are developed in a top-down manner by applying a set of processes that can easily be integrated into the framework.

4.2.7. *Electronic commerce*

AMS should follow an incremental implementation strategy that minimizes investment risks and disruptions to ongoing production. The plan is to get a baseline AMS service up and running as rapidly as possible. Next, the system should be augmented using E-mail access via interactive hypermedia. Then the prototypes of directory, brokering, bidding and CAD format translation services should be established. The prototype brokering and bidding service will match buyers and sellers of fabrication services and other commodities. Customers and providers will use semi-formal E-mail to post and retrieve messages on a bulletin board that is organized into appropriate commercial categories. Then the process is to integrate AMS client software directly into CAD and CAM environments. An engineer, working at a CAD system, should be able to pull down a menu and send a design directly to a fabrication service, requesting a preliminary cost estimate and a DFM analysis. In parallel with these improvements to the information system design, the AMS team should continue refining the Virtual Company business model. Suppliers and other potential members should be invited to participate in the refinement and further planning activities.

IT alone does not guarantee responsiveness, either at the enterprise level or at the site-facility level. For small-lot, rapid response manufacturing services, machine set-up and changeover times are recognized as the major cost drivers. The AMS partners should agree to work jointly on developing technology that will minimize setup and changeover times. Significant opportunities for improvement should be identified in areas such as fixture configuration, part setup, part and process verification, cutting tool management, and simplified shop documentation. These issues, while specific to machining, are representative of the process-related problems that should be solved in every manufacturing domain to achieve agility. Current manufacturing system design methodologies produce multiple models of the eventual agile manufacturing system. These models reflect either the designers view of some subsystem, like materials handling, some level of abstraction, or some developmental stage in the design of the system. These models serve to break the complex system design into smaller, more manageable size problems (Parks *et al.* 1994). The following are the characteristics of IT in agile manufacturing systems:

- Customer interactive computer systems that allow the customer or her/his representative to configure a design.
- Groupware that enables people located remotely from each other to work co-operatively.
- Greatly improved multimedia human-interface systems.
- Enterprise-wide concurrency that covers all the functions of a company.
- Electronic commerce on international multimedia networks.
- Widespread use of networked distributed databases.
- Software ‘agents’, or ‘burrowing’ programs, which will constantly look for data on a network, look for requests for proposals to reply to, order items, continuously update network-based catalogues, etc.

- More open information systems in companies that will make information much more widely and openly accessible than it is today.
- Software and computers that are much more powerful than those available today, which will enable rapid and powerful simulation and modelling to be carried out for the analysis and approval of designs and production plans.
- Better mathematical understanding of representation methods used in design.
- Agreed communication and software standards.

5. Conclusions

In this paper, an attempt has been made to (i) study the scope of the agile manufacturing, (ii) develop a conceptual model for illustrating the various concepts and enablers of agile manufacturing, and (iii) present a framework for the development of an agile manufacturing system. The issues of agility have been discussed from different perspectives, but the main focus has been on the enablers of agile manufacturing for enhancing the competitiveness of manufacturing organizations. The manufacturing concepts, e.g. JIT, TQM and BPR, and technologies, e.g. FMS, CIM, and Automated Storage and Retrieval Systems (AS/RS) can be utilized to achieve agility in manufacturing. Also, other concepts, e.g. design for engineering, quality and manufacturing, will facilitate the development of an agile manufacturing system. Manufacturing performance measures using ABC and non-financial measures, e.g. quality, innovation, flexibility, inventory and productivity, would help in designing a most effective agile manufacturing system. Quantitative models should be developed for evaluating agility and related trade-offs.

The future manufacturing strategy for 'agile manufacturing enterprise' should be in the following directions: (i) co-operative work among small and medium enterprises to utilize the advantage of the capability of each company for mutually profitable projects; (ii) companies have to organize themselves as teams to take advantage of market opportunities; (iii) re-engineering of the business process to facilitate an effective communication and integration of various partner-firms. The world of agile manufacturing is already coming into being. Ten and 20 years from now, the agile-manufacturing system will appear as natural to the next generation of industrial managers who follow us, as the mass-production system does now (Preiss 1994). The following are some of the research directions for practitioners and researchers interested in further investigation in agile manufacturing. The list is by no means exhaustive.

(i) A method for effectively forming a partnership in an agile manufacturing environment is to be developed.

(ii) Multi-functional workforce and their performance evaluation should be studied in agile manufacturing. Furthermore, the nature of training and education in agile manufacturing should be precisely defined. Suitable mathematical models need to be developed for determining the numbers of workers required in an agile environment.

(iii) Based on the nature of information and material flows in an agile manufacturing enterprise, a more precise model and organizational structure for agile manufacturing should be developed.

(iv) Performance measurement and investment justification in an agile manufacturing environment need to be investigated. Also, a method to evaluate the selection and performance of partner-organizations is essential.

(v) An investigation of the selection of suitable architectures for agile manufacturing systems would offer further insights into the design of agile manufacturing. Also, appropriate capacity planning and scheduling methods are to devised to support the agile manufacturing.
(vi) A quality management system should be developed for assurance of quality in an agile environment.
(vii) A suitable cost accounting system should be established to measure the cost of a product and decide about the product-mix in an agile manufacturing environment.
(viii) The scope and applications of the concept of agility in service industries need further investigation.
(ix) Empirical research is required to study the application of the model developed in this paper and to characterize agile manufacturing.

Currently, the author and his team at Brunel University are conducting research on some of these agile manufacturing research problems. It is hoped that this paper will further reinforce the on-going research, and offer potential research directions for developing and operating on agile manufacturing organization.

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