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Agile manufacturing: a taxonomy of strategic and technological imperatives

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Agile Manufacturing (AM) is a relatively new operations concept that is intended to improve the competitiveness of firms. Manufacturing/service processes based on AM are characterized by customer-supplier integrated processes for product design, manufacturing, marketing, and support services. Agile manufacturing requires enriching of the customer; cooperating with competitors; organizing to manage change, uncertainty and complexity; and leveraging people and information. In recent years, a number of research papers have been published in the area of AM. The term 'agile' was coined in 1991. However, there are still some serious concerns that prevent companies from taking an entirely different direction from AM. Considering the potential importance of agile manufacturing in 21st century manufacturing competitiveness, an attempt has been made in this paper to re-examine the scope, definitions and strategies of AM. In addition, a framework has been presented as a basis for understanding the major strategies and relevant technologies of AM.

1. Introduction

Businesses are restructuring and re-engineering themselves in response to the challenges and demands of the 21st century. The 21st century business will have to overcome the challenges of customers seeking high-quality, low-cost products, and be responsive to customers' specific unique and rapidly changing needs (Bunce and Gould 1996). Agile enterprises represent a global industrial competition mode for 21st century manufacturing. 'Agility' addresses new ways of running companies to meet these challenges. In a changing competitive environment, there is a need to develop organizations and facilities that are significantly more flexible and responsive than existing ones (Gould 1997, James-Moore 1996).

Agility requires 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 (Cho *et al.* 1996). 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; and (vii) electronic commerce (Gunasekaran 1998).

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Agile manufacturing is a vision of manufacturing that is a natural development from the original concept of 'lean manufacturing'. In lean manufacturing, the emphasis is on the elimination of waste. The requirement for organizations and facilities to become more flexible and responsive to customers led to the concept of 'agile' manufacturing as a differentiation from the 'lean' organization. This requirement for manufacturing to be able to respond to unique demands moves the balance back to the situation prior to the introduction of lean production, where manufacturing had to respond to whatever pressures were imposed upon it, with the risks to cost, speed and quality. Agility should be based on not only responsiveness and flexibility, but also the cost and quality of goods and services that the customers are prepared to accept. It is, however, essential to link agile capabilities in manufacturing with product needs in the marketplace. Agility as a concept increases the emphasis on speed of response to new market opportunities. Thus, it is more relevant to a One-of-a-Kind Product (OKP) than it is to commodity products that compete primarily on price. This paper makes an attempt to link strategy with potential technological solutions to achieve agility in manufacturing organizations. Although the focus of this paper is on the concept of agility, broad focus should (encompassing the virtual organization) be on the 'Agile Supply Chain'. This aspect has been considered throughout the paper.

Several research reports have been published on agile manufacturing. However, there has only been limited study on a comprehensive analysis of agile manufacturing, its feasibility in real-life organizations, strategies and technologies and on some future research directions that will enable the success of agility in manufacturing. Considering the relevance of the paradigm, an attempt has been made in this paper to re-examine the scope, definition and strategies of agile manufacturing. This analysis is based on the review of literature available on agile manufacturing.

The organization of the paper is as follows. Section 1 presents the scope of agile manufacturing. The concepts and definitions of agile manufacturing are presented in section 2. Section 3 deals with the strategies and technologies of AM. In section 4, a framework is offered for developing an Agile Manufacturing System (AMS). Section 5 concludes the paper.

2. Agile manufacturing—definitions

In this section, we explore a variety of definitions and a range of concepts with the objective of developing a new and feasible concept of AM. The reason for analysing the present conceptions and definitions of AM is to identify the gap between practice and theory in order to enhance the confidence of practitioners. Manufacturing processes based on agile manufacturing are characterized by customer integrated processes for designing, manufacturing, marketing, and support for all products and services; decision-making at functional knowledge points; stable unit costs; flexible manufacturing; easy access to integrated data; and modular production facilities (Abair 1997). The focus is on the integration of critical functional areas with the help of advanced design and manufacturing technologies, and alignment between strategies.

According to Gupta and Mittal (1996), AM is a business concept that integrates organizations, people and technology into a meaningful unit by deploying advanced information technologies and flexible and nimble organization structures to support highly skilled, knowledgeable and motivated people. 'Lean' implies high productivity and quality, but it does not necessarily imply being responsive. 'Agile', on the other hand, stresses the importance of being highly responsive to meet the 'total needs' of the customer, while simultaneously striving to be lean—a manufacturer whose primary goal is to be lean compromises responsiveness over cost-efficiencies. Agile manufacturers place equal importance on both cost and responsiveness. This is the main reason for incorporating cost and quality into agile competitive bases (Yusuf *et al.* 1999).

Agile manufacturing can be said to be a relatively new, post-mass-production concept for the creation and distribution of goods and services. It is the ability to thrive in a competitive environment of continuous and unanticipated change and to respond quickly to rapidly changing markets driven by customer-based valuing of products and services (DeVor and Mills 1995). It includes rapid product realization, highly flexible manufacturing, and distributed enterprise integration. DeVor and Mills (1995) argue that technology alone does not make an agile enterprise. Companies should find the right combination of strategies, culture, business practices, and technology that are necessary to make it agile, taking into account the market characteristics.

As stated before, agile manufacturing is driven by the need to respond quickly to changing customer requirements. It demands a manufacturing system that is able to produce effectively a large variety of products and to be reconfigurable to accommodate changes in the product mix and product designs. Manufacturing system reconfigurability and product variety are critical aspects of agile manufacturing. The concept of agility has an impact on the design of assemblies. To implement agile manufacturing, methodologies for the design of agile manufacturing are needed. Design for agile assembly is accomplished by considering the operational issues of assembly systems at the early product design stage (Kusiak and He 1997).

According to Tu (1997), the manufacturing industry, particularly the OKP (One-of-a-Kind Production) industry, tends to be lean, agile and global. This tendency leads to a new concept of a virtual company that consists of several subproduction units geographically dispersed in the world as branches, joint ventures and subcontractors. Many OKP companies, such as those in shipbuilding have become virtual companies. For these virtual companies, traditional production control and management systems, methods and theories do not satisfy their needs for production planning and control. For some companies, therefore, there is a need to be transformed into a virtual enterprise in order to become agile. However, selecting partners based on flexibility and responsiveness alone will not lead to a reduction in cost and an improvement in the quality of products and services. A much wider spectrum of factors needs to be taken into account.

Agile manufacturing is an expression that is used to represent the ability of a producer of goods and services. The changes needed for agile manufacturers to thrive in the face of continuous change can occur in markets, in technologies, in business relationships and in all facets of the business enterprise (DeVor *et al.* 1997). Such changes, according to Kidd (1996) are not about small-scale continuous improvements, but an entirely different way of doing business. Agile manufacturing requires one to meet the changing market requirements by suitable alliances based on core-complementary competencies, organizing to manage change and uncertainty, and leveraging people and information (Gunasekaran 1998, 1999a, Yusuf *et al.* 1999).

The analysis of various definitions and concepts of AM (see table 1) show that all these definitions are polarized in a similar direction. Most definitions and concepts

Authors	Definition	Keywords
DeVor and Mills (1995)	Ability to thrive in a competitive environment of continuous and unanticipated change and to respond quickly to rapidly changing markets driven by customer-based valuing of products and services.	A new, post-mass production systems for the creation and distribution of goods and services.
Booth (1996), McGrath (1996)	More flexible and responsive.	Moving from lean to agile
Adamides (1996)	Responsibility-based manufacturing (RBM).	Most adjustments for process and product variety to take place dynamically during production without *a priori* system reconfiguration.
Gupta and Mittal (1996)	Agile stresses the importance of being highly responsive to meet the 'total needs' of the customer, while simultaneously striving to be lean. Agile places a higher priority on responsiveness than cost-efficiency while a manufacturer whose primary goal is to be lean compromises responsiveness over cost-efficiencies.	Integrates organizations, people, and technology into a meaningful unit by deploying advanced information technologies and flexible and nimble organization structures to support highly skilled, knowledgeable and motivated people.
James-Moore (1996), Kidd (1996), Gould (1997)	More flexible and responsive than current.	New ways of running business, casting off old ways of doing things.
Hong *et al.* (1996)	Flexibility and rapid response to market demands.	Flexible technologies such as Rapid Prototyping, Robots, Internet, AGVs, CAD/CAE, CAPP and CIM, FMS.
Abair (1997)	Provides competitiveness.	Customer-integrated process for designing, manufacturing, marketing and support, flexible manufacturing, cooperation to enhance competitiveness, organizing to manage change and uncertainty and leveraging people and information.
Kusiak and He (1997)	Driven by the need to quickly respond to changing customer requirements.	Demands a manufacturing system to be able to produce efficiently a large variety of products and be reconfigurable to accommodate changes in the product mix and product designs, Design for assembly.
Gunasekaran (1998)	Capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets.	Virtual Enterprise, E-Commerce, Strategic Partnership formation, and Rapid prototyping.
Cho *et al.*, (1996), Gunasekaran (1999a), Yusuf *et al.* (1999)	Capability for surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets.	Standard Exchange for Product (STEP) models, Concurrent Engineering, Virtual Manufacturing.

Table 1. A summary of agile definitions and key concepts.

seem to highlight flexibility and responsiveness as well as virtual enterprises and information technologies. However, the question is whether one can achieve agility with minimum investment in technologies and processes. Hence, there is a need to redefine the definition of agility within this context. Figure 1 presents the new model for explaining the agile manufacturing paradigm. The model takes into account the characteristics of the market, infrastructure, technologies and strategies. Its purpose is to highlight the new dimension of the definition of the agile manufacturing paradigm. The justifications for the need to redefine the agility are listed below.

(1) In some cases, flexibility and cost are not complementary. Yet, there is a need to consider the *cost* aspects of agility. Agility without cost effectiveness is not a real competitive strategy. Therefore, there is a need to consider cost in defining agility.
(2) The implications of technologies in achieving agility are paramount compared with partnership formation that is based on core competencies in a virtual enterprise. For certain businesses one needs to identify a set of technologies that are more important to the selected market segments, and to product and service requirements. Yet, the implications of integrating complementary core competencies are highly significant. A lack of focus on utilizing core competencies would not improve productivity and quality.
(3) The nature of a given market certainly defines the characteristics of agile organizations. No organizations can satisfy unlimited product/service requirements of different markets. The characteristics of markets may vary from industry to industry and from country to country.
(4) The implications of e-commerce have not been properly addressed in the development of agile manufacturing systems. Direct input from customers,

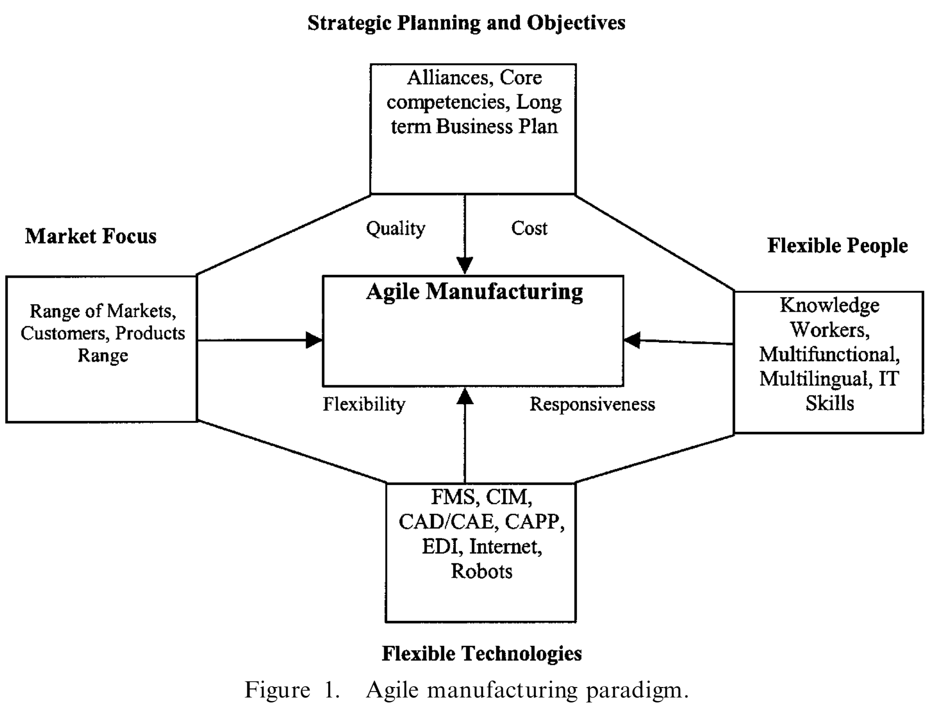

Figure 1. Agile manufacturing paradigm.

the reduction in response time and the cost of identifying market requirements using Concurrent Engineering principles would certainly reduce the gap between marketing and production.

(5) Human resources play a significant role in the development of agile manufacturing systems. However, the issue of an agile workforce has not been well addressed. It is still not clear how the agility of the workforce and its characteristics can be defined with reference to changing market requirements and value-adding systems.

(6) Logistics play an important role, especially in physically distributed virtual enterprises. Therefore, due attention should be paid to the effective management of logistics and, in turn, to supporting agility in manufacturing.

Based on some of these observations, Agility in manufacturing may be defined as:

> The capability of an organization, by proactively establishing virtual manufacturing with an efficient product development system, to (i) meet the changing market requirements, (ii) maximize customer service level and (iii) minimize the cost of goods, with an objective of being competitive in a global market and for an increased chance of long-term survival and profit potential. This must be supported by flexible people, processes and technologies.

3. Agile manufacturing strategies and technologies

In this section, the literature available on AM has been reviewed based on the classification of major strategies and technologies of AM. The objective of such a review is to identify the major strategies and technologies and the gap between the current and future manufacturing strategies. Also proposed is the list of most appropriate strategies and technologies that should be given due attention in developing a practical and feasible concept of AM. The summary of the review, based on these two criteria, is presented in Appendix I. Analysing the overall characteristics of strategies and technologies, the literature available on AM can be grouped under the following themes: (i) strategic planning, (ii) product design, (iii) virtual enterprise, and (iv) automation and Information Technology (IT). The details of the classification are illustrated in figure 2.

Achieving agility may require focusing on strategic planning, product design, virtual enterprise and automation and IT. Table 2 shows the classification of AM literature and the corresponding references. It is important to mention that the literature surveyed in this paper is not exhaustive, but only representative.

3.1. *Strategic planning*

Strategic planning of performance improvement is gaining attention in all areas of manufacturing. The reason for this is that it takes into account the long-term interest of the company in determining suitable business and operational policies. To achieve agility in manufacturing, several sub-strategies are needed, including virtual enterprise, rapid-partnership formation, rapid prototyping, and temporary alliances based on core competencies. Without suitable business and operations strategies, technologies and systems alone are not sufficient to achieve agility. Agile manufacturing can be achieved through customer-integrated multidisciplinary teams, supply chain partners, flexible manufacturing, computer-integrated information systems, and modular production facilities (Abair 1997, Sharifi 1998).

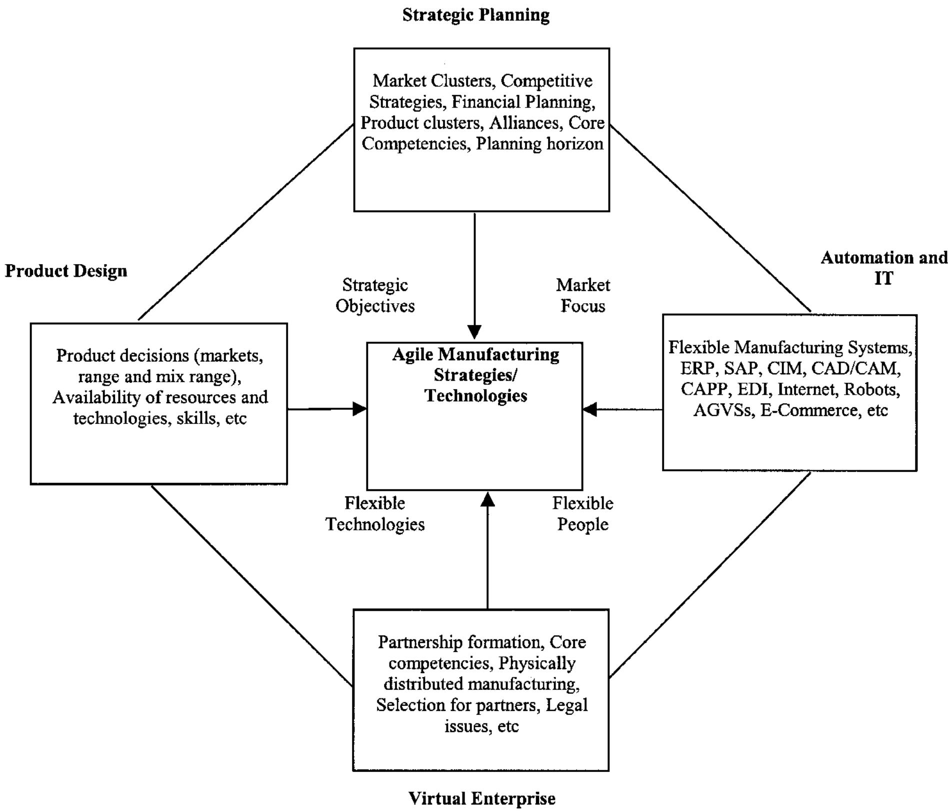

Figure 2. Agile manufacturing strategies/techniques.

As the complexity of the market and production increases on a global scale, new extended enterprise objectives, drivers, performance indicators and boundary conditions are being defined within the framework of agile manufacturing. Whilst the needs of extended enterprises have been identified to a large extent, there is a lack of suitable and commercially available tools to satisfy these needs. Therefore, a new generation of tools should be developed and the existing tools significantly enhanced to support decision-making processes and to deliver required solutions to extended businesses. This presents both a challenge and an opportunity to information technology (IT) and hence the communications industry is to play a major role in agility (Walters 1997).

Current approaches to the design and construction of enterprise systems lead to fixed interdependencies between valuable resources. This constrains the resource reuse and the agility of systems, often preventing close alignment between system behaviour and business process requirements. Weston (1998a, b) describes the important role that software-based integration infrastructures and integration structures, respectively, can play in supporting and organizing system behaviour in a way that facilitates system extension and change. Such a software-based system is likely to become a common building block of next-generation agile manufacturing systems.

The necessity of maintaining lean operations and becoming an 'agile enterprise'—in which the speed and flexibility at which a company functions match

Criteria	References	Strategies/Methods/Technologies
Strategic Planning	Adamides (1996), Pellew (1996), Forsythe and Ashby (1996), McMullen (1996), Abair (1997), Medhat and Rook (1997), Tu (1997), Forsythe (1997), Walters (1997), Weston (1998), Noori and Mavaddat (1998), Gunasekaran (1998), Gunasekaran (1999), Yusuf *et al.* (1999)	Extended enterprise, Temporary strategic alliances, Response-based manufacturing, virtual enterprise, Information Technology, Advanced manufacturing concepts and technologies, performance measures (ABC and ABM) to be proactive. Software for integration, supply chain management, Integration of functions, Innovation, Competitive conscious, Knowledge workers, Employee empowerment, Top management support, Concurrent product development
Product Design	Candaida *et al.* (1995), Medhat and Rook (1997), Monsplaisir (1997), Kusiak and He (1997), Lee (1998), Subbu *et al.* (1998a, b), Gunasekaran (1998, 1999a, 1999b)	Virtual design environment, Automated high level process planning, Design for agility, DfM, DfA, Group Technology, Standard Exchange for Products (STEP), CSCW Prototype, CAD/CAE
Virtual Enterprise	Abair (1995), Bocks (1995), Mills (1995), Herrmann *et al.* (1995), Gupta and Nagi (1995), Tracy *et al.* (1994), Hessney (1997), Lee (1997), Orady *et al.* (1997), Gunasekaran (1998, 1999a)	Integration of core competencies, Supply chain, Temporary alliances, System integration, Modular structure, Prequalifying partners/partner selection, Data Management Framework
Automation and Information Technology	Graham and Ragade (1994), Hong *et al.* (1996), Wang *et al.* (1996), Yang (1996), Adamides (1996), Quinn *et al.* (1996), Ashley (1997), Medhat and Rook (1997), Kim *et al.* (1997), Lee *et al.* (1997), Erdel (1997), Mathieu (1997), Song and Nagi (1997), Jo *et al.* (1997), Kirk and Tebaldi (1997), Merat *et al.* (1997), Langford and Scheuermann (1998), Ahmed (1998), Ayoyama (1998), Wang *et al.* (1998)	Internet, EDI, E-Commerce, Real-time object-oriented software environment, CAD/CAE, CAPP, MRP II, ERP, Multimedia, Robots, AGVSs, NC machines, CCD, VMEbus control system, WWW, WAIN, SAP< ASEE, CNC, IMS, OOM, Simulation, Object-Oriented Model

Table 2. Summary of AM literature and key observations.

those of its technology—is generally accepted. Information technology is providing the means for companies to integrate better their internal and external activities. This level of integration is achieved through ‘Enterprisewide systems’ that reflect the current operations and processes of the business and allow decision-makers to digest information more rapidly and accurately, and with more flexibility (Noori and Mavaddat 1998).

Responsibility-based manufacturing (RBM) is a new architecture of production systems that falls under the umbrella of the AM paradigm. In mass-customization environments, RBM allows most adjustments for process and product variety to take place dynamically and rapidly during production without the need for *a priori* system reconfiguration. Active resources (mobile robots, intelligent pallets, etc.) take the responsibility for the production of individual parts/products, thus implementing the unitary relation, individual customer to individual producer. As different products are produced at the same time to achieve a coherent and augmented team performance, coordination of active resources is obtained by exploiting the relations that hold among the activities of the individual product and process plans (Adamides 1996).

An integrated supply chain can act as a global network used to deliver products and services from raw materials to end-customers through an engineered flow of information and physical distribution. The supply chain management system focuses on resolving business process problems that are important to customers. The supply chain can facilitate flexibility and responsiveness of an organization. The characteristics and correlation, such as quality, services and competitive consciousness centred on customers, innovatory characteristics, human-based integration and the leading technology for the AM model, should be considered.

For virtual companies, traditional methods of production planning and control (PPC) do not satisfy their needs for operations management. The following aspects are to be considered for PPC in AM environments: (1) modelling of evolutionary and concurrent product development and production under continuous customer's influence; (2) real-time monitoring and control of the production progress in a virtual company; (3) a flexible or dynamic company control structure to cope with uncertainties in the market; (4) an adaptive production scheduling structure and algorithms to cope with uncertainties of the production state in a virtual company; (5) modelling of production states and control systems in a virtual company; and (6) reference architecture for a virtual company (Tu 1997).

An appreciation of the human factors inherent in agile product development is pivotal to the successful integration of agility-enabling technologies, as well as the coordination of personnel working within a CE environment. Forsythe (1997) briefly summarizes human factors contributions to: (1) development of agile business practices; (2) design of enabling technologies; and (3) management of introduction and fielding of new technologies and business practices. Forsythe also discussed human factors related to the communications and information infrastructure that is essential to an organization making the transition from traditional to agile product development. In addition, knowledge workers should be flexible, taking into account the responsibility of multiple tasks and communicating in multi-lingual modes in the physically distributed environment of the AM enterprise.

Gunasekaran (1998, 1999a, b) and Yusuf *et al.* (1999) highlight the role of employee empowerment in improving the cooperative supported work in a physically distributed Virtual Enterprise (VE). Achieving agility in manufacturing requires radical changes in line with a productive reengineering business process. This level of change in any organization demands the total support of top management in terms of providing necessary technical and financial support together with employee empowerment. As part of multidisciplinary-empowered and self-directed teams, a human factors practitioner can be asked to assume leadership of the communications team with the task of developing an information infrastructure to support a product development project structure and the facilitation of information flow in a large, geographically dispersed, project team. This responsibility should reflect recognition of the importance of human interactions in an information-driven product development process (Forsythe and Ashby 1996). In addition, top management involvement is vital to effective re-engineering of the supply chain and logistics in agile environments (Pellew 1996).

As producers, wholesalers and retailers seek more effective ways of marketing their products, they increasingly examine their supply chains for ways to reduce costs. The logistics supply chain aims to achieve improved flexibility by reduced supply cost, reduced stock holding costs, removal of stock rooms and increased selling space for retailers, control of inbound materials, integration of functions from purchasing to sales, and increased control of the supply chain (Pellew 1996). For an agile supply chain, top management involvement is vital to reengineer effectively the supply chain and logistics. In agile supply chain environments, the relationship with suppliers and the interaction between suppliers should be flexible in terms of delivering products/services and responsiveness.

McMullen (1996) shows how the philosophies, practices, decision processes, measurements, logistics, and systems architectures of the Theory of Constraints (TOC) all work together to provide an infrastructure for AM. It is suggested that TOC systems can be moved to a co-standard status with traditional MRP/Capacity requirements planning (CRP) systems, in order to encourage the systems community to provide the MRP II and ERP systems infrastructure required to support the emerging agile manufacturers.

One of the major issues that should be resolved is the performance measures and metrics suitable for selecting partners based on temporary alliances and changing market needs. Since responsiveness is the key objective, companies may demand a set of simple performance measures in developing AMSs based on both the financial and non-financial performance measures. CE can be used as a tool for the optimal selection of partners by aligning appropriate strategies in an agile supply chain with the help of information analysis tools, such as Quality Function Deployment (QFD). Suitable frameworks should be established to develop a management system for an agile manufacturing enterprise incorporating the information flow and performance measurements.

The articles reviewed under strategic planning for AM deal with issues such as VE and strategic alliances (partnership formation) based on core-competencies, responsive logistics, rapid product design, and flexible computer systems. Since the system should be proactive to changes in the market requirements, there is a need for long-term policies. The major issues in developing AM are how the resources can be reconfigured/reused to meet the challenges of market dynamism, technological advancements, infrastructure, government policies and legislation. In most cases, the overall objective is to minimize the capital expenditures and the cost of resources in meeting the changing market requirements with the objective to enhance the market share or profit level. In AM enterprises, strategies can be formulated based on a top down approach and they could be implemented using a bottom-up approach. Therefore, issues such as market types, strategic alliances, and capital investment decisions should rely on the top management whilst the implementation rests on the functional level managers and employees (Gunasekaran, 1998, 1999a).

3.2. *Product design*

The agile manufacturing system should be able to produce a variety of components at low cost and in a short time period. Lee (1998) formulated a design for agility rule. The design rule reduces manufacturing lead times in consecutive changes of product models. Along with changes of product models, machines are relocated considering the overall costs of material handling and reconfiguration.

Medhat and Rook (1997) examine the role of enabling processes and techniques, such as Computer Aided Design (CAD) and Computer Aided Engineering (CAE), and formal methods, such as Design for Manufacture and Assembly, to achieve reduced product development cycles, whilst improving the quality of products. The authors highlight the implementation plans and pitfalls and the challenges that the organization faces in implementing a Concurrent Engineering (CE) strategy.

Agility in manufacturing requires a change around the formation of product development teams. These teams include representatives with different expertise, such as design, manufacturing, quality assurance, purchasing, marketing, field service and support. Change has also included relaxing those policies that inhibited design changes and providing greater authority and responsibility to members of design teams. Managing change in a manufacturing environment requires a more systematic method of concurrently designing both the product and the downstream processes for production and support. Medhat and Rook (1997) discuss the need to achieve a multi-disciplinary team-working environment as a prerequisite for facilitating a CE strategy.

Agile manufacturing requires a rapid product design system with the objective of switching over to new products as quickly as possible. This, in turn, needs a system to group various resources and products to reduce the non-value adding activities and hence the time to reach market with the right products at the right time. Candadai *et al.* (1995) discuss a variant approach for quick design evaluation in an AM environment. Their approach uses a STEP-based product model to generate the Group Technology (GT) code of a candidate product design, and additional information critical to the product's manufacture. This information is used to conduct an efficient search for similar products manufactured by potential partners and to obtain useful feedback on manufacturing processes, production times, costs, and quality attributes of these products. Such feedback is valuable for design evaluation and improvement early in the design cycle of a product in AM.

Monplaisir (1997) describes the evaluation of two Computer-Supported Cooperative Work (CSCW) prototypes to aid engineering teams in the design of an AM facility. The CSCW considers a large number of flexibility and agility criteria associated with the design of manufacturing systems. Both prototypes support functions such as anonymous inputs, parallel processing of information, group memory, electronic brainstorming, and consensus building.

As discussed earlier, both hardware and software reconfigurability are required to achieve agility in manufacturing. Kusiak and He (1997) developed software using the rules applicable to the design of products for agile assembly from an operational perspective. These rules are intended to support the design of products to meet the requirements of AM. In order to reduce time to market, CE principles can be employed in a product development process in AM enterprises.

Virtual Design Environment (VDE) is an information architecture to support design-manufacturing-supplier-planning decisions in a distributed heterogeneous environment. The approach utilizes evolutionary intelligent agents as program entities that generate and execute queries among distributed computing applications and databases. The evolutionary agents support a global evolutionary optimization process in which successive populations systematically select planning alternatives that reduce cost and increase throughput. A prototype of the virtual design environment has been implemented by Subbu *et al.* (1998a) using CORBA as a principal distributed systems programming tool. The prototype has been used to examine design-manufacturing-supplier decisions for a real commercial electronic circuit board product (Pitney Bowes) and to explore plans in controlled experiments with alternative manufacturing facilities.

3.3. *Virtual enterprise*

A virtual organization is the integration of complementary core competencies distributed among a number of carefully chosen, but real organizations all with similar supply chains focusing on speed to market, cost reduction and quality (Abair 1995). Generally, a single organization often may not be able to respond quickly to changing market requirements. Temporary alliances or partnerships based on core competencies of firms will help to improve the flexibility and responsiveness of organizations. However, co-ordination and integration could be complicated. Appropriate strategies and methodology, which will involve communication, training and education, and goal deployment, must be adopted for an effective coordination and integration of participating firms at different levels of cooperation (Gunasekaran 1998, 1999a).

Virtual Manufacturing (VM) is an integrated synthetic-manufacturing environment used to enhance all levels of decision and control in a manufacturing enterprise. The agile enterprise requires VM to respond to changing market requirements quickly. VM environments are being proposed to improve responsiveness, improve product and process design, reduce manufacturing risks, improve manufacturing design and operation, support manufacturing system changes, enhance product service and repair, increase manufacturing understanding, and provide a vehicle for manufacturing training and research. The VE environment places a number of special requirements on the process design activity. Since virtual enterprises are temporary, such organizations must be easily assembled and disassembled. Individual partner organizations do not cease to exist during their membership of the VE. This point highlights another important issue, that of security. Security matters require appropriate industrial legislation and legal protection to be established (Gunasekaran, 1998).

Agility imposes special requirements on the information systems used to run an enterprise. In addition to satisfying the traditional requirements, an agile enterprise information system should be able to reconfigure in a very short time and to include parts of information systems from other companies if a Virtual Corporation was required to meet the market demand. The traditional, common shared database model of integration has severe problems in this environment. The Systems Integration Architecture (SIA) project is based on a new transformation model of integration and provides sets of high level services, which allow information system modules, including foreign modules, to be rapidly reconfigured. These services include the management of information (naming, locations, format, files structure and data access type) as well as the relationships among data sets, communications between objects on heterogeneous computer systems, wrappers for legacy software, diverse control approaches, composition of modules into processes and user interfaces. SIA also allows for the integration of functions and control as well as data (Mills 1995).

As noted earlier, partnership formation based on core-competencies and temporary alliances facilitate agility in manufacturing. In partnership development, there is a need for information on three functions of AM that include prequalifying partners, evaluating a product design with respect to the capabilities of potential partners, and selecting the optimal set of partners for the manufacture of a given product (Medhat and Rook 1997). In particular, Herrmann *et al.* (1995) present an information model that describes the systems, process capabilities, and performance of an AM firm.

Agile manufacturing combines the strengths of qualified partners in a virtual organization to meet a given market need. High level process planning is a way to aid designers to improve their design with respect to the capabilities of potential partners. An automated high level process planning system for mechanical components developed by Gupta and Nagi (1995) considers both global and partner-specific manufacturing capabilities so that cost, cycle time, and quality attributes can be derived for a given design. The system generates a set of manufacturing operations and candidate partner plants that can contribute to the manufacture of candidate design. The most promising process plans resulting from this process may be used to select the most suitable partners for the VE.

The global supply chain management system includes external Enterprise Resource Planning (ERP). 'Thoughtware' and *GroupWare* with 'legacy systems' focusing on *MRP II* fundamentals such as global sales and operations planning can be used to analyse and optimize an entire supply chain from purchasing/suppliers through *AM* using a streamlined logistics network and overcoming cultural, communications, and cross-functional obstacles (Hessney 1997). The cultural, communication and cross-functional obstacles can be overcome in a VE by training and education, strategic alliances, advanced information technologies to improve the communication, and team working by empowered employees. To be truly agile, supply partners should be able to move even more quickly and have efficient utilization of the existing equipment, existing facilities and even existing designs (Tracy *et al*. 1994).

Lee (1997) has discussed the reconfigurability of a manufacturing system, which is important in achieving agility in manufacturing. This discussion is based on the relationship between component routes, material handling costs, reconfiguration cost, and so on. Components with similar routes are selected in an early design stage in order to minimize the number of machines to be relocated. The variety of resources required is reduced by a proper selection of components and manufacturing processes for system reconfiguration. Information Technologies such as Internet, CAD/CAM, MRP, ERP, EDI, EC can be employed for an effective integration of physically distributed firms in AM enterprises. Flexible simulation software systems will surely enhance the effectiveness of VEs in a physically distributed manufacturing environment and hence the agility in manufacturing. For example, Virtual Reality Software (VRS) for robotics and manufacturing cell simulation can be employed to obtain a three-dimensional (3D) graphics model for manufacturing lines. The 3D graphics model will help facility planners to visualize the system before constructing it, make alternative designs, program robot paths, obtain layouts for the systems, obtain data for the discrete event simulation, and develop the cell control program (Orady *et al*. 1997). As indicated earlier, virtual enterprises require high-level communication systems to eliminate non-value adding activities in the supply chain. This also helps to avoid human related errors in exchanging information and controlling operations in AM environments.

Supply chain management in VE needs a different set of frameworks, strategies, techniques and performance measurement criteria. For example, the relationship with suppliers in lean organizations is based on long-term focusing on cost reduction. In the case of AM, however, the relationship is temporary, focusing on responsiveness. Therefore, appropriate supply chain management strategies, methods and performance measurements should be established to improve the effectiveness of supply chain management in AM enterprises.

3.4. *Automation and Information Technology*

Agile manufacturing needs intelligent sensing and decision-making systems capable of automatically performing many tasks traditionally executed by human beings. Visual inspection is one such task and hence there is a need for effective automated visual inspection systems in AM environments (Enke and Dagli 1997). Agile manufacturing requires agile-enabling technologies such as virtual machine tools, flexible fixturing, and agile design alternatives (Ashley 1997). As pointed out earlier, physically distributed manufacturing environments/VEs demand high-level communication systems such as Internet, EDI and Electronic Commerce to exchange information at various levels of manufacturing organizations. Flexible fixturing is a key technology in the integration of AMS and the lack of effective flexible fixturing can be a significant obstacle to implementation (Hong *et al*. 1996).

System integration in AM is complicated because of the nature of a virtual and physically distributed enterprise. To be true to its concept, AM needs to adopt the principles of all process advancements evolving out of machine tool and cutting tool technology and their related scientific fields (Erdel 1997). Medhat and Rook (1997) examine the role of enabling processes and techniques such as CAD/CAM/CAM to reduce product development cycles. Agile manufacturing requires an intelligent CE design support system that can provide rapid evaluation of engineering designs and design changes. Often, this process results in modified products that require adjustment and retooling of the manufacturing processes that produce the product (Graham and Ragade 1994).

The systems for AM should include mostly software/decision support systems for various planning and control operations including materials requirements planning, design, manufacturing resource planning, scheduling, and production planning and control. Based on the nature of AM environments, we discuss the various control systems required for AM environments. There are several computer-integrated systems that could be used for AM, some of them are as follows: (i) MRPII, (ii) Internet, CAD/CAE, (iii) ERP, (iv) Multimedia, and (v) Electronic Commerce.

In a global manufacturing environment, IT plays a dominant role of integrating physically distributed manufacturing firms. AM can be supported by enabling technologies such as robotics, Automated guided vehicle systems (AGVSs), Numerically Controlled (NC) machine tools, CAD/CAM, rapid prototyping tools, Internet, World Wide Web (WWW), Electronic Data Interchange (EDI), Multimedia and Electronic Commerce (Candadai *et al*. 1994, Cho *et al*. 1996). For example, a virtual enterprise relies on these technologies. Some of the key agile-enabled technologies include mobile robots, intelligent pallets, and flexible fixtures. Strategic, tactical and operational performance measures should be considered in assessing the impact of alternatives with the objective of selecting the most suitable technologies. Adamides (1996) reviews the technology involved in RBM and discusses the qualitative and quantitative performance characteristics of its coordination mechanism.

Agile manufacturing requires a rapid changeover from the assembly of one product to the assembly of a different product. This in turn needs a rapid hardware changeover by robots, flexible part feeders, modular grippers, and modular assembly hardware (Hong *et al*. 1996). The division of assembly, feeding, and unloading tasks between multiple robots should be examined with prioritization based upon assembly time. A real-time, object-oriented software environment utilizing graphical simulations for offline software development will facilitate rapid software changeover. An innovative dual Virtual Manufacturing Enterprise bus (VMEbus) controller architecture permits an open software environment while accommodating the closed nature of most commercial robot controllers. These agile features permit new products to be introduced with minimal downtime and system reconfiguration. For instance, Quinn *et al.* (1996) discussed a design for AM workcells intended for light mechanical assembly of products made from similar components (i.e. parts families). Flexible fixturing is a key technology in the integration of agile manufacturing systems and the lack of effective flexible fixturing can be a significant obstacle to implementation. Ahmed (1998) presents a concurrent framework for the integration of automated fixture design and automated fixture assembly activities, which are essential requirements for efficient and agile manufacturing technologies.

Merat *et al.* (1997) have proposed an agile workcell for light mechanical assembly. The workcell includes multiple robots, a conveyor system, multiple flexible parts feeders at each robot's workstation, Computer-Controlled Digital (CCD) cameras for parts feeding and hardware registration, and a dual VMEbus control system. A flexible parts feeder design uses multiple conveyors to separate the parts and machine vision to locate them. Object-oriented software (C++) running under V $\times$ Works, a real-time operating system, can be used for workcell control. In this way, agile software architecture was developed for a rapid introduction of new assemblies through code reuse. Specialized hardware will be encapsulated on modular grippers and modular worktables that can be quickly interchanged for assembly of different products (Merat *et al.*, 1997). Global access to people, data, software, documents and multimedia have allowed organizations to shorten the development cycle for new products, communicate with experts from all over the world, improve manufacturing processes, and receive immediate customer feedback (Mathieu 1997).

The need to reconfigure rapidly an agile manufacturing system makes it especially difficult to test the system's control software. Although thorough testing is essential for system reliability, the time available for testing may be short. With a simulator, however, the software can be developed and tested independently from the actual workcell, while production continues or the workcell is reconfigured for the next target product (Jo *et al.* 1997). Cheng *et al.* (1998) discuss the potential benefits, and the future applications of AI- and Internet-based agile manufacturing technology in industry.

Aoyama (1998) proposed a fundamental redesign of the software development process, called the Agile Software Process (ASP) to meet the conflicting demands of delivering software products faster while simultaneously facilitating their widely distributed development. Two methods, the time-based process enacting model and just-in-time process management are embedded into a process-centred software engineering environment called Prime, and a Web-based information-sharing environment, Wide-Area Information Network (WAIN) to ease the operations of ASP. Together with other software engineering tools, Prime and WAIN form the network-centric Agile Software Engineering Environment (ASEE).

Wang *et al.* (1996) present an Internet assisted manufacturing system for AM practice. This system uses the Internet as an interface between a user and the Central Network Server (CNS) and allows a local user to operate remote machines connected to the Internet. It consists of a CAD/Computer-Aided Process Planning (CAPP)/CAM/Computer Aided Analysis (CAA) integrated CNS, which links to local Flexible Manufacturing Systems (FMSs), or Computer Numerically Controlled (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 machine to accomplish the whole production process.

The flexibility of an AMS can be achieved in part through computer software. The system's control software must be adaptable to new products and to new system components without becoming unreliable or difficult to maintain. This requires designing the software specifically to facilitate future changes. Kim *et al*. (1997) have developed a software architecture for control of an AM workcell, and have demonstrated its flexibility with a rapid changeover and introduction of new products. AMSs can benefit significantly from a database support for partner selection, and mistake proofing.

The next-generation intelligent manufacturing systems (IMSs) will be multi-agent systems containing distributed control and application entities that dynamically collaborate to satisfy both local and global objectives. The research in this area focuses on development of a generic control system designer based on IEC-1499 function block standards, for real-time distributed manufacturing environments (Wang *et al*. 1998).

Song and Nagi (1997) proposed a framework for production control in an AM environment in which: (1) information is modelled in a hierarchical fashion using object-oriented methodology (OOM); (2) information transactions are specified by the workflow hierarchy consisting of partner workflows; (3) information flow between partners is controlled by a set of distributed workflow managers (WM) interacting with partner knowledge bases, which reflect partner specific information control rules on internal data exchange, as well as inter-partner mutual protocols for joint partner communications; and (4) the prototype system is accomplished using the WWW based on a client-server architecture.

4. A framework for the development of agile manufacturing

In this section, a framework for the development of agile manufacturing is presented. This is based on the review of reported literature and some case examples as discussed in the previous sections. The conceptual model and the summary of strategies, methods and technologies presented in table 2 are used to develop the framework. In this framework, some of the practical issues of agility in manufacturing are addressed consistent with the modified concepts and definition of agile manufacturing. There are several tools and methods that have been proposed to develop an agile manufacturing system. For example, Yang (1996) proposed an object-oriented model of an AMS with definitions of the agile objects at four levels and their features. Furthermore, the model explains the process in which the agile objects, under the stimulation of tasks (market demands), get assembled into objects at higher levels and are integrated into agile systems by sending information to each other and by accepting information selectively. The object-oriented method can be adopted to study the agile system and its working mechanisms. The framework proposed here constitutes the following major strategies and technologies for achieving agile manufacturing:

- Partnership formation and supplier development
- IT in manufacturing.
- Enterprise Integration and Management with the help of advanced IT/IS.

- Virtual reality tools and techniques in manufacturing.
- The application of most of the advanced manufacturing concepts and technologies, such as Computer-Integrated Manufacturing/Services, Manufacturing/Service Strategy, Enterprise Integration, Rapid Prototyping, CE, New Product Development, BPR, Systems Design and Operations and SCM.
- Global manufacturing/service perspectives (physically distributed manufacturing environments) with the help of IT, such as E-Commerce, ERP, SAP, Internet, WWW, CAD/CAM, Simulation, Multimedia and MRPII.

4.1. *Strategic planning*

For virtual agile manufacturing, temporary alliances and integration of complementary core competencies is a necessity. Therefore, based on a given demand along the supply chain, there is a need to select partners based on their involvement in the value-adding chains. Development of VE requires the following: (i) a framework for the corporate strategy formulation process based on global competitiveness for manufactured goods and services, (ii) a decision support system for selecting suitable partners based on the required core competencies, (iii) an IT-based SCM system for controlling operations in VE, and (iv) performance measurement system for continuous improvement in an AM environment. Existing methods and tools can be used for strategy formulation and selecting partners for AM enterprise development. Marketing research would help to identify the competitive performance objectives, based on which agile strategies can be formulated. Moreover, VR tools and techniques could be used to make a quick decision based on the more accurate data analysis.

CE within a fast-paced product development environment favours collaborative work between engineering disciplines. Certain challenges of human factors posed by the agile environment can be overcome by a series of team meetings during which the team jointly develops the project plan, including objectives, strategies for meeting objectives, a detailed task network, schedule and resource and funding projections. The information technologies alone are not sufficient to achieve the desired communications efficiency and, if anything, the unfamiliarity of the technologies could impede communications efficiency (Gunasekaran 1999a).

Agile manufacturing has different requirements for the workforce as compared with traditional systems, and they are: (i) closer interdependence among activities, (ii) different skill requirements, usually higher average skill levels, (iii) more immediate and costly consequences of any malfunction, (iv) output more sensitive to variations in human skill, knowledge and attitudes and to mental effort rather than physical effort, (v) continual change and development, and (vi) higher capital investment per employee, and favour employees responsibility for a particular product, part or process (Pinochet *et al*., 1996). These, to some extent, define the characteristics of an agile workforce and the training and education required, which include IT-skilled workers, knowledge in team working and negotiation and advanced manufacturing strategies and technologies, empowered employees, multifunctional workforce, multilingual workforce, and self-directed teams (Abair 1995, Forsythe and Ashby 1995, 1996, Forsythe 1997).

An agile organization should posses the capability of a learning organization. For this purpose, IT can be used along with a suitable organizational structure that promotes innovation and training and education. In a global manufacturing environment, the communication should be standardized for improving the cooperative supported work in a VE. This requires a standard computer-aided communication system with suitable changes to suit the local environment, such as translation into a different language. In addition, the agile manufacturing can be achieved by suitable strategic alliances based on mergers and acquisitions with the objective of obtaining required services. Other external factors, such as type of the market and products, location, government policies and environmental regulations need to be considered in the strategic planning for the suitability of AM and its development.

4.2. *Product design*

The reduction of product development cycle time is important in an agile manufacturing environment to meet the changing market requirements by suitably reconfiguring the available resources and developing suppliers. Generally, a major portion of the manufacturing cycle time is shared by product development time. Reducing the product development cycle time is a major task in AM. For this, concepts/techniques such as CE, DfM, DfA, DfQ and QFD, and technologies such as CAD/CAE, Virtual Design Environment and Rapid prototyping can be used. Even when a design firm is contracted for high quality design products/services, it still needs to interact with all other partners along the value-adding chain of the VE. In order to achieve this, a multi-firm cooperation in line with a multidisciplinary team for reducing the overall product development cycle time is required. Online data gathering (such as E-Commerce) could be used to learn more about exact customer/market requirements.

4.3. *Virtual enterprise*

It is essential to develop VE in a more productive way by reducing the time and cost as well as delivering goods/services in a competitive manner in global markets. The following steps can be employed for developing a VE: (a) identify the corporate objectives; (b) based on the multiple manufacturing performance objectives, identify the product/service requirements from suppliers; (c) select partners based on the core competencies using a suitable supplier ranking system; (d) using the time scale, which should be rather short, link it all as a VE with the help of automation and IT. In addition, the human resource management should be given due attention while developing VE for AM. A Data Management Framework (DMF) to support agility in manufacturing is needed (Bocks 1995). A DMF has been defined as the ability of an enterprise to manage distributed data, information, and knowledge as the decisive enabler for core enterprise business processes. The purpose of DMF is to provide a seamless enterprise data management solution in support of the AM environments. It must be stressed, however, that such seamless data integration is potentially complex. Integration of current fragmented computer systems, causing over-complexity, is perhaps the biggest challenge the AM enterprise faces.

In the AM environment, information can be transmitted via multiple channels depending on urgency, content and distribution through phone, voice-mail, fax, e-mail, and http (Forsythe 1997). The agile workforce should be capable of meeting increasing technological challenges, designing their workplaces, solving quality-related problems and team-to-team learning, improving equipment availability, using mistake-proofing processes, dealing with increased complexity, and finally, helping labour unions harmonize their members and company expectations (Plonka 1997).

In a VE, the nature of training and education should have a different focus compared with that of traditional organizations. For example, an international team of empowered employees and self-directed teams should be developed with a view to improve the effectiveness of a globally distributed manufacturing enterprise. This requires the understanding of the culture and language of each other together with sufficient literacy in computerized information analysis and synthesis. GroupWare has been used as a group decision-making environment to assist teams evaluating a quality function deployment framework for risk management and agile manufacturing system designs (Monplaisir *et al.* 1997).

4.4. *Automation and Information Technology*

Automation and IT play a predominant role in the development of a physically distributed enterprise. The role of automation and IT can be identified in several areas of the development process. The most important are (i) strategy formulation, (ii) tactical management, (iii) operations control and (iv) systems. For example, the concepts of AM can be validated using computer-aided simulation and a full scale-manufacturing cell (Kirk and Tebaldi 1997). From the review of agile-enabling technologies, it can be noted that the selection of technologies for achieving agility in manufacturing depends upon the strategies that are selected to meet changing market requirements. For example, JIT may require EDI, FMS may need AGVs, Robots and NC machine tools whilst agility heavily relies on virtual manufacturing/enterprise or physically distributed manufacturing environments. Suffice to state that technologies such as IT, manufacturing cells, robots, flexible part feeders, modular assembly hardware, automated visual inspection systems, virtual machine tools, flexible fixturing, CAD/CAM and automated high-level process planning are essential for developing agile manufacturing systems (Gunasekaran 1998, 1999a).

An object-oriented model of an Agile Manufacturing System with a definition of the Agile Objects at four levels and their features will be useful (Monplaisir 1997). In addition, it explains the process in which the Agile objects, under the stimulation of tasks (market demands) get assembled into objects at higher levels and are integrated into an agile system by sending information to each other and by accepting information selectively. Various organizational processes should be tested for their ability to meet the changing market requirements. Co-operative supported work for rapid prototyping is required to assist an engineering team in the design of an agile manufacturing facility. The prototype systems should support the following: autonomous inputs, parallel processing of information, group memory, electronic brainstorming and consensus building. Suitable algorithms should be developed and tested for the computer supported cooperative work (CSCW).

4.5. *Aligning agile strategies and technologies*

In this section, an attempt has been made to link business strategy and potential technological solutions. We have made explicit aligning technological 'solutions' with the business strategy so that the problems of selection, prioritization and implementation can be addressed. In addition, we show how the framework reported here can be used to develop an agile manufacturing system in practice.

Table 3 provides some generic guidelines for strategies and technologies with the objective of achieving agile manufacturing. For example, one of the major charac-

Agile enterprise characteristics	Strategies	Technologies
Quick Response Manufacturing	Virtual Enterprise, Supplier Development, Partnership Development	Rapid Prototyping, Internet, WWW, E-mail
Flexible Organization	Group Technology (GT), Manufacturing Cells, Concurrent Engineering	Robots, AGVs, NC Machines, CAD, CAPP, and CIM
Learning Organization	Matrix Organizational Structure, Strategic Alliances, Systems Thinking, Knowledge Management and Transfer, Change of Culture, Empowerment, Team Work	Information Technology, Groupware, Internet, E-Commerce, Multimedia
Integrated Value Chain	Supplier Development	MRP, ERP, SAP, Internet, E-Commerce
Physically Distributed Manufacturing Environment	Lean Manufacturing, FMS and JIT	Knowledge workers, Learning Organization
Mass Customization	Flexible Resources	GT, EDI, CAD/CAM/CAPP, E-Commerce
Reconfigurability	Virtual Enterprise, Flexible Resources	CE, STEP, CIM

Table 3. Linking agile strategies with technologies.

teristics of an agile organization is the quick response or the speed with which it can respond to changing market requirements. It requires strategies such as alliances based on core competencies, physically distributed manufacturing environment, Supply Chain Management and technologies such as Internet, Enterprise Resource Planning (ERP) systems and SAP. Similarly, reconfigurability is an essential characteristic of agile organizations. Reconfigurability depends upon the nature of the organizational resources, including information systems, human resource skills available and other capital resources. GEC Marconi Aerospace (GECMAe) implemented certain agile technologies with the objective of improving the agility in the organization. For example, GECMAe has implemented CE and EDI for improving the quality of design and to minimize the total cycle for manufacturing aerospace products (Gunasekaran *et al.* 2000).

It was also noted that, for GECMAe, there is a *breakpoint* between being a fully agile and a fully lean company. A recommendation has been made to apply a 'lean mindset' to the long-established products that are currently within the maturity stage of the product life cycle in order to reduce unit costs, while new products could lend themselves to a more agile approach (Gunasekaran *et al.* 2000). Currently, there are many firms that have to be agile because the life cycle of their products is short. The example of mobile phones is given to note the fact that companies can be six months behind in developing new models, while the customers in this market are very demanding. For the established products at GECMAe, the lifecycles can be quite long, with numerous designs on the order books for the next ten years—hence full-agility is not required! This is not to say that agile manufacturing is totally inapplicable. Quite the opposite; various enablers of agile manufacturing (e.g. Electronic Commerce, Supply Chain Management, Enterprise Resource Planning Systems, Integrated Product/Production/Business Information Systems, and Concurrent

Engineering) are quite useful to employ in a company such as GECMAe. Changes are being made in light of the overall business perspective and market—not necessarily to become more agile, but simply because it *makes sense* to change! GECMAe has the right philosophy, in that, there is no point buying the latest technology if reengineering or efficiency improvements can achieve the same desired end result (Gunasekaran *et al.* 2000).

4.6. *Research issues/problems in implementing the agile technologies*

The following are the research issues/problems in implementing some of the agile technologies such as E-Commerce, ERP, SAP, BAAN, Oracle, E-Business, Internet, WWW, Rapid Prototyping, AGVs, EDI, CAD/CAPP, CAM and CIM.

- It is essential to identify the agile dimension of different industries and then suitable strategies, methods and technologies with the objective developing a framework for agility in those industries.
- A study of the role of top management knowledge and support of agile manufacturing and its technologies would help set budget priorities and strategic alliances for acquiring enabling technologies of agile manufacturing.
- An investigation is required on the compatibility of different information technologies that include legacy systems, client-server technologies, ERP, Oracle, SAP, Operating Systems, etc.
- It is not clear yet what sort of training and education is required in motivating the employees to take part in the development of AM.
- The justification of investment in various agile technologies is important, with the objective of maximizing the return and achieving agility that would improve the competitiveness of firms.
- Empirical or case study research may be helpful in deciding the type and level of training necessary for the successful implementation and application of agile technologies.
- Since the requirement of the type of agile technologies depends upon the business process structure, there is a need to study the alignment between business process and agile technologies so that effective enterprise integration can be achieved for improved organizational competitiveness.
- The impact of organizational infrastructure, systems and technologies on the partnership selection and supplier development should be studied with the objective of improving agility.
- An empirical investigation is required to study whether agility is a critical factor for success in different industries that include transportation, aerospace products, electronic components, machine tools, and consumer product industries.
- The importance of data mining and data warehousing need to be investigated while selecting suitable agile technologies.

4.7. *Importance of strategic and technical imperatives*

The strategic approach for agility is important considering global competitiveness and the global nature of manufacturing. For example, some industries, such as the consumer products industry, may not require agility to compete in the international market. However, the automobile, electronic and software industries require agility in their manufacturing in order to compete in a global e-market. Agile technology requirements may force some companies to align with certain companies with the objective of acquiring necessary agile technologies as well as business process compatibility.

In a virtual enterprise or extended enterprise development, the availability of agile technologies is a determinant in selecting suitable partners and suppliers. The main objective of the strategies and technologies is to improve the agility level in an organization. Alignment between strategies and organizational infrastructure would require suitable technologies and skills and these are particularly important in the global agile manufacturing environment. Necessary changes should be made to the business process in case the technology available has limited scope in its application. Nevertheless, the technologies should be easily updated or easily migrated to the next level of systems so that the benefits of new technologies can be utilized for improving the agility with the objective of competing in a dynamic global market environment.

Looking at the strategies and technologies available for developing AMS, the following are the most important: (i) a virtual enterprise, (ii) strategic alliances based on core competencies, (iii) learning organization, (iv) CAD/CAE/CAM and (v) Information Technology.

5. Summary and conclusions

In this paper, an attempt has been made to review the literature on AM with the aim of revising the outlook for agility in manufacturing and identifying corresponding major strategies and technologies of AM. In addition, a framework has been offered in the paper to develop an AMS.

Two key characteristics of manufacturing companies discussed in this paper are 'Agility'—the ability of a company to effect changes in its systems, structure and organization—and 'Responsiveness'—the ability of a company to gather information from its commercial environment and to detect and anticipate changes, to recover from changes and to improve as a result of change. Manufacturing companies, even those operating in relatively stable conditions with good market positions, are facing fast and often unanticipated changes in their commercial environment. Being agile in such environments means being flexible, cost effective, productive and producing with consistent high quality. Each company will respond in a specific and different way deploying its own agile characteristics. The problem of identifying, analysing and evaluating agility is that no commonly accepted practical frame of reference or analytical structure exists.

The literature available on an AM workforce is rather limited. The reason for this is that there is no clear-cut framework for identifying the implications of AM on workforce characteristics, and most of the literature deals with enabling technologies and some strategies of AM. However, human factors play a significant role in the successful development and implementation of AM. The key issues of human factors that need to be considered in agile environment are knowledge workers, multilingual workforce, multinational workforce, incentive schemes, type and level of education and training, relation with unions, and pay award.

Most of the available systems (control and information) are developed for traditional manufacturing environments where a static market behaviour and resources have been employed for producing goods and services. The support systems for AMS rely heavily on computer-based information systems such as EDI, Internet and Electronic Commerce. Therefore, a flexible architecture for systems to accommodate temporary alliances will help improve enterprise integration and hence agility in organizations.

The following is the summary of issues that should be addressed in an attempt to fully embrace agile manufacturing: (i) the implications of temporary alliances on the enterprise communication and coordination, (ii) the influence of a virtual enterprise and physically distributed manufacturing on human relations management, and (iii) the technologies and human skills required for the information intensive manufacturing environment. Agile Manufacturing/Service requires *multidisciplinary* skills, which include manufacturing management, computer science, operational research, software engineering, systems design, sensors, mechatronics, robotics, systems integration, virtual manufacturing/services, enterprise integration and management and *Advanced Information Technologies*. The major problems that need most attention in the development of AM are: (1) modelling of evolutionary and concurrent product development and production under a continuous customer's influence; (2) real-time monitoring and control of the production progress in virtual OKP; (3) a flexible or dynamic company control structure to cope with uncertainties in the market; (4) an adaptive production scheduling structure and the algorithms to cope with the uncertainties of a production state in virtual OKP; (5) modelling of production states and a control system in virtual OKP; and (6) the reference architecture for a virtual OKP company (Tu 1997).

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Appendix A: Agile manufacturing strategies/techniques and technologies

References	Agile strategies	Agile technologies
Abair (1995)	Virtual organization, supply chain, temporary alliances	Information Technology, CAE, MRPII
Gupta and Nagi (1995)	Virtual organization	Automated high level process planning system, CAD, CAPP, Virtual Reality
DeVor and Mills (1995)	Product Design, Distribution of goods	Flexible Manufacturing Systems, Data Communication, and Data Processing, Wide Area Network (WAN)
Herrmann *et al.* (1995)	Temporary alliances based on core-competencies, optimal set of partners, design evaluation	Information technology, Computer-Aided Design, Decision Support Systems

Cho *et al.* (1996)	Standard for the Exchange of Products, Product Model, Concurrent Engineering	Prototyping Software, Control Systems, Information Technology
Hong *et al.* (1996)	Flexible tooling, Flexible fixturing	Operations Research models, IT
Abair (1997), Gunasekaran (1998, 1999a), Yusuf *et al.* (1999)	Virtual enterprise, rapid-partnership formation, rapid prototyping, alliances based on core competencies, multidisciplinary teams, supply chain partners, flexible manufacturing, computer-integrated manufacturing and modular production facilities	Internet, E-Commerce, Computer-Supported Co-operative work, Flexible Manufacturing Systems, Information Technologies such as multimedia, Internet, Database, Electronic Data Interchange, Computer-Aided Design, Computer-Aided Engineering, Computer-Aided Process Planning, etc.
Harrison (1997)	Flexible Manufacturing, Virtual Organizations, Supply Chain	Flexible Manufacturing Systems
Tu (1997)	Virtual Company, One-of-a-Kind Production (OKP), Joint Ventures, and Subcontractors	Computer-Integrated Manufacturing Systems
Kusiak and He (1997)	Design for manufacturability, design for assembly	Flexible Manufacturing Systems, Systems Analysis
Medhat and Rook (1997)	Concurrent Engineering, Product design, Quality assurance	Computer aided design, Computer aided manufacturing, Computer aided software engineering
Fromson (1997)	Virtual enterprise, Legal aspects	Flexible Manufacturing Systems, Computer Systems
Pellew (1996)	Supply chain management, Logistics, Integrating purchasing, Top Management Support, Reengineering, Supplier Development	Flexible Manufacturing Systems
Hessney (1997), Tracy *et al.* (1994)	Global Supply Chain Management, Communication, Cross Functional Interaction	Enterprise Resource Planning (ERP), Equipment Utilization
Adamides (1996)	Responsibility-Based Manufacturing (RBM), Distributed decision making, Heterarchical coordination, System reconfiguration	Flexible Manufacturing Systems, Robots, Control Systems, Intelligent agents
Quinn *et al.* (1997)	Agile manufacturing workcells	Flexible part feeders, Modular assembly hardware, Rapid hardware changeover, Rapid software changeover
Ahmed (1998)	Concurrent Engineering, Constraint theory, Computer simulation	Computer Applications, Fixtures (tooling), Concurrent Engineering, Machine Tool Accessories
Pasek and Szuba (1998)	Automotive Applications, Open Architecture, Integration of functions	Smart line tools, real-time control, sensor signals, computer controls,

(*continued*)

Appendix A—*concluded*

Enke and Dagli (1997)	Automation and Intelligent Systems, Visual Inspection, Computer integrated manufacturing, Artificial intelligence, Intelligent manufacturing, Computer Aided Manufacturing	Flexible manufacturing system, Computer vision, Automated misplaced component inspection, Intelligent visual inspection, Semiconductor Devices & Integrated Circuits
Merat *et al.* (1997)	Computer integrated manufacturing, Flexible Manufacturing, Robot Applications	Flexible manufacturing systems Grippers, Industrial robots, Conveyors, Computer vision, Flexible parts feeders
Lee (1997)	Computer aided manufacturing, Optimal Routing and Sequencing in the Design of products	Flexible manufacturing systems
Orady *et al.* (1997)	Virtual reality, Computer software, Robotics, Manufacturing, data processing	Computer simulation, Three dimensional computer graphics
Mathieu (1997)	Internet, World Wide Web (WWW), Computer Applications	Flexible Manufacturing Systems, Data Communication, Equipment & Techniques, Database Systems
Jo *et al.* (1997)	Computer integrated manufacturing, Control systems, Program debugging, Computer simulation, Virtual reality	Flexible manufacturing systems, Three dimensional computer Graphics, Computer aided software engineering
Cheng *et al.* (1998)	Artificial intelligence, Computer aided design, Computer aided Manufacturing, Concurrent engineering	Flexible manufacturing systems, Wide area networks, Internet
Walters (1997)	JIT production, Wide area networks, Extended enterprises, World Wide Web (WWW), Internet	Flexible manufacturing systems, Information Technology, Voice/data communication systems
Aoyama (1998)	Agile software process (ASP), Agile software engineering environment (ASEE), Computer Applications, Data Communication	Digital Computers & Systems
Subbu *et al.* (1998a, b)	Decision support systems, Virtual reality, Computer integrated manufacturing, Artificial intelligence	Computer systems programming, Computer aided design, Database systems, Virtual design environment, Evolutionary optimization
Yang (1996), Kirk and Tebaldi (1997)	Flexible manufacturing systems, Tooling design, Robotic Cellular Manufacturing	Flexible manufacturing systems, Object oriented programming, Process engineering
Bocks (1995)	Information management, Computer aided manufacturing	Information Technology
Wang *et al.* (1996)	CAM, Flexible Manufacturing, Reengineering	CAD/CAM/CAPP and Internet
Candadai *et al.* (1995)	Process control, Product design, Quality assurance, Group technology	Flexible manufacturing systems

Monsplaisir (1997)	Computer Supported Cooperative Work (CSCW) Prototypes, Parallel Processing of Information, Electronic Brainstorming	Information Technology
Kim *et al.* (1997)	Information Technology	Software Architecture for control of AM
Wang *et al.* (1998)	Flexible Manufacturing Systems, Computer Aided Manufacturing	Next-generation intelligent manufacturing systems, Multi-agent Systems, Expert Systems
Song and Nagi (1997)	Enterprise Integration, Partner Integration	Object-oriented methodology, ERP, EDI and C-Commerce, WWW
Mills (1995), Weston (1998)	Virtual Corporation, System Integration Architecture	Information Systems, Heterogeneous computer systems, legacy software
McMullen (1996)	Theory of Constraints (TOC)	MRP/CRP and ERP
Plonka (1997), Nechyba and Xu (1997), Forsythe (1997), Forsythe and Ashby (1996), Pellew (1996)	Knowledge workers, multilingual workforce, incentive scheme and union-management relationship	Employee participation, Training and Education, Skills in Computers
Gunasekaran (1998, 1999), Yusuf *et al.* (1999), Pinochet *et al.* (1996), Abair (1995)	Top management support	Communication, workshop, benchmarking exercise, Training and Education