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Int. J. Production Economics 62 (1999) 87–105

international journal of  
**production  
economics**

www.elsevier.com/locate/dsw

# Agile manufacturing: A framework for research and development

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## Abstract

Agile manufacturing (AM) is a new concept in manufacturing intended to improve the competitiveness of firms. Manufacturing processes based on AM are characterized by customer–supplier integrated process for product design, manufacturing, marketing, and support services. This needs decision-making at functional knowledge levels, stable unit costs, flexible manufacturing, easy access to integrated data, and modular production facilities. Agile manufacturing requires enriching of the customer, co-operating with competitors, organizing to manage change, uncertainty and complexity, and leveraging people and information. In the recent years, a number of research papers have been published in the area of AM. However, a framework for the development of AM has not received due attention from both researchers and practitioners. Realizing the importance of agile manufacturing in the 21st century manufacturing competitiveness, an attempt has been made in this paper to review the literature available on AM with the objective to: (i) identify key strategies and techniques of AM, (ii) suggest some future research directions and (iii) develop a framework for the development of agile manufacturing systems (AMSs) along four key dimensions which include strategies, technologies, systems and people. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* Agile manufacturing; Review; Future research; Development; Framework

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## 1. Introduction

Businesses are restructuring and re-engineering themselves in response to the challenges and demands of 21st century. The 21st century businesses will have to overcome the challenges of demanding customers seeking high quality, low cost products, responsive to their specific and rapidly changing

needs [1]. Agility addresses new ways of running companies to meet these challenges. Agility is about casting off those old ways of doing things that are no longer appropriate – changing pattern of traditional operation. In a changing competitive environment, there is a need to develop organizations and facilities significantly more flexible and responsive than current existing ones [2,3].

Agile manufacturing can be defined as the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services [4]. Agile manufacturing is not

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about small-scale continuous improvements, but an entirely different way of doing business [5]. Agile manufacturing is a new expression that is used to represent the ability of a producer of goods and services to thrive in the face of continuous change. These changes can occur in markets, in technologies, in business relationships and in all facets of the business enterprise [6]. Agile manufacturing requires to meet the changing market requirements by suitable alliances based on core-competencies, organizing to manage change and uncertainty, and leveraging people and information.

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 cost-cutting. The requirement for organizations and facilities to become more flexible and responsive to customers led to the concept of the '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 on it, with the risks to cost and quality. The move to lean production from agile and vice versa is a major challenging task [7,8].

Most of the literature tends to focus on a few enablers/strategies of AM without a comprehensive framework for achieving AM. In most cases, those agile strategies and techniques are disconnected. Such a comprehensive framework can be developed either by field studies or by a systematic literature survey to identify the key strategies and techniques of AM and then integrate them to develop an AMS. Since AM is at the developmental phase, it is worthwhile to develop the idea based on existing studies. Therefore, literature survey is the adopted methodology in this paper for the development of a framework for an agile manufacturing system (AMS).

The organization of the paper is as follows: Section 2 presents the classification of the literature available and a brief review of the previous research on AM. Comments on the literature and future research directions are discussed in Section 3.

A framework for the design of AM is presented in Section 4. Section 5 concludes the paper.

## 2. Classification and a review of previous research on agile manufacturing

In this section, a classification of the literature available on AM and a brief review of each article are presented. Agile manufacturing includes rapid product realization, highly flexible manufacturing, and distributed enterprise integration. Technology alone does not make an agile enterprise. Every company must find the right combination of culture, business practices, and technology that are necessary to make itself agile. In this paper, the focus is on the operating conditions of factories organized as flexible networks of processors based on core competencies. With this scope in mind, an attempt has been made in this section to review the literature on AM.

### 2.1. Classification of the literature on agile manufacturing

The literature available on AM has been classified based on the nature and the focus of agile enablers which include criteria such as strategies, technologies, systems and people. A classification scheme based on the nature and application of the models is proposed for easy understanding of the research work on AM. The literature available under each criterion have been further grouped under sub-classification to improve to the clarity of the presentation and highlight some key factors of AM under each classification. The main objective of this particular classification is to develop a suitable framework for AMSs along these four dimensions/criteria. Agility should be in all areas of manufacturing to effectively respond to changing market requirements. Achieving agility therefore requires flexibility and responsiveness in strategies, technologies, people and systems. Table 1 shows the classification of the literature on AM and the corresponding references on the basis of strategies, technologies, systems and people. It is imperative to mention that the literature surveyed in this paper are not exhaustive, but only a representative.

Table 1  
Classification of agile manufacturing literature

Criteria for classification of the literature	Sub-classification	References
Strategies	Virtual enterprise	[9–17]
	Supply chain	[1,5,7–9,18–22]
	Concurrent engineering	[7,17,20,23–26]
Technologies	Hardware – tools and equipments	[19,24,27–35]
	Information technologies	[4,17,19,31,33,34,36–40]
Systems	Design systems	[25,27,41–50]
	Production planning and control systems	[15,16,42,49,51]
	System integration and database management	[1,15,17,24,36,37,39,46,51–56]
People	Knowledge workers	[17,56,57]
	Top management support and employee empowerment	[17,21,58,59]
	Training and education	[9,17,44,56,57,59,60]

## 2.2. Review of literature on agile manufacturing

In this section, the literature available on AM has been reviewed based on the classification scheme shown in Table 1. The stated articles have been reviewed for the key strategies adopted, technologies used, organizational issues and human resource development in AM. For the purpose of brevity, the review of each article has been kept to highlighting the key strategies and techniques suggested by authors.

### 2.2.1. Strategies

Strategic approach to 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. Agile manufacturing itself is a strategy. To achieve this, several sub-strategies are needed including virtual enterprise, rapid-partnership formation, rapid prototyping, and temporary alliances based on core competencies. Without suitable strategies, technologies and systems alone not sufficient to achieve agility. Agile manufacturing requires customer integrated multidisciplinary teams, supply chain partners, flexible manufacturing, computer-integrated information systems, and modular production facilities [61]. In this section, some of the key strategies of AM have been identified for the review

of literature and further details are presented hereunder.

*2.2.1.1. Virtual enterprise.* A virtual organization is the integration of core competencies distributed among a number carefully chosen but real organizations all with similar supply chain focusing on quick to market, cost reduction and quality [9]. Generally, a single organization is often may not be able to respond quickly to changing market requirements. Temporary alliances or partnership based on core competencies of firms will help to improve the flexibility and responsiveness of organizations. However, co-ordination and integration are complicated in this environment. Appropriate strategies/methods such as communication, training and education, and strategic alliances can be adopted for an effective co-ordination and integration of participating firms at different levels of co-operation.

Virtual Manufacturing (VM) is an integrated, synthetic manufacturing environment exercised 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 their 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 Virtual Enterprise (VE) environment places a number of special requirements on the process design activity. Since virtual or distributed enterprises are temporary, such organizations must be easily assembled and disassembled. Individual partner organizations do not cease to exist during their membership in the VE. This point highlights another important issue, security. These require appropriate industrial legislation and legal protection to be established [17].

Today, the manufacturing industry particularly the One-of-a-Kind Production (OKP) industry, tends to be lean, agile and global. This tendency leads to a new concept of a virtual company that consists of several sub-production units geographically dispersed in the world as branches, joint ventures and sub-contractors. Many OKP companies, such as those in the heavy industry, for example a shipbuilding company, have become virtual companies [16]. Another example is that construction industry has practised VEs for a number of years. The manufacturing also has become of more service oriented industries. Therefore, some of the successful strategies and techniques used in construction such as for partnership formation can also be implemented for the development of AM.

As noted earlier, partnership formation based on core-competencies and temporary alliances facilitate agility in manufacturing. In the partnership formation, 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 certain product. In particular, Herrmann et al. [12] 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 certain 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 has been developed by Gupta et al. [10] that 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 the candidate design. The most promising process plans resulting from this process may be used to select the most suitable partners for the VE. The article reviewed under VE highlights the communication and performance measurement as the key issues for developing an effective AMS.

*2.2.1.2. Supply chain.* A supply chain is the 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 the customers.

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 [21]. For agility in supply chain, top management involvement is vital to effectively reengineering supply chain and logistics. In agile supply chain environments, relationship with suppliers and interaction between suppliers should be flexible in terms of delivering products/services and responsive. Appropriate frameworks should be established to develop a management system for agile manufacturing enterprise incorporating the information flow and performance measurements.

The global supply chain management includes 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 analyze and optimize an entire supply chain from purchasing/suppliers through AM using a streamlined logistics network and overcoming cultural, communications, and cross-functional obstacles [22]. The

barriers of 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 must be able to move even more quickly and with more efficient utilization of the existing equipment, existing facilities and even existing designs [18].

Responsibility-Based Manufacturing (RBM) is a new architecture of production system 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 which hold among the activities of the individual product process plans [19].

Agility in supply chain can be achieved by integrating organizations, people, and technology into a meaningful unit by deploying advanced information technologies and flexible organizational structures to support highly skilled, knowledgeable, and motivated people. Although the words agile and lean are sometimes used interchangeably in this context, they are not the same. Lean implies highly cost-efficient and productive, although 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. Thus, an agile manufacturer places a higher priority on responsiveness than cost-efficiency while a manufacturer whose primary goal is to be lean, compromises responsiveness over cost-efficiencies [53].

Supply chain management in VE needs 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. But

in the case of AM, 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.

*2.2.1.3. Concurrent engineering.* Agility in manufacturing requires a change around the formation of product development teams. These teams have included representatives with different expertise, such as design, manufacturing, quality assurance, purchasing, marketing, field service and support. Change has also included relaxing 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. This systematic approach is fundamentally known as Concurrent Engineering (CE). Mehdad and Rook [26] discuss the need to achieve a multidisciplinary team working environment as a prerequisite for facilitating a CE strategy. They also examine the role of enabling processes and techniques such as Computer Aided Design, Computer Aided Engineering and formal methods such as Design for Manufacture and Assembly, to achieve reduced product development cycles, whilst improving the quality of products.

Agile manufacturing 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. The manufacturing system reconfigurability and product variety are critical in AM. The concept of agility has an impact on the design of assemblies. To implement AM, methodologies of design for AM are needed. Design for agile assembly is accomplished by considering operational issues of assembly systems at the early product design stage [25].

Agile manufacturing requires an intelligent engineering design support system that can provide rapid evaluation of engineering designs and design changes. Often this process results in modified products that require adjustments and retooling of

the manufacturing processes that produce the product. Graham and Ragade [23] discuss the requirements for an intelligent CE design support station that will allow the design engineer to evaluate design modifications while concurrently examining suitability for manufacturing.

The articles reviewed under strategies 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. However, the main focus is on the virtual enterprise, strategic alliances and enterprise integration with computerized information 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 and procured to face 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 should be formulated based on top down approach and they should be implemented using bottom-up approach. Therefore, issues such as market types, strategic alliances, capital investment decisions should rely on the top management and the implementation rests on the functional level managers and employees.

### 2.2.2. Technologies

In a global manufacturing environment, information technology plays a dominant role of integrating physically distributed manufacturing firms. Critical to successfully accomplishing AM are a few enabling technologies that include robotics, Automated Guided Vehicle Systems (AGVSs), Numerically Controlled (NC) machine tools, Computer-Aided Design (CAD)/Computer-Aided Manufacturing (CAM), rapid prototyping tools, Internet, World Wide Web (WWW), Electronic Data Interchange (EDI), Multimedia and Electronic Commerce [4]. For example, virtual enterprise relies on technologies such as VM, CAD/CAM, and Information Technology (IT)

(including multimedia, rapid prototyping, Internet, Electronic Commerce). Some of the key agile-enabled technologies include mobile robots, intelligent pallets, and flexible fixtures, and strategic, tactical and operational performance measures are to be considered in assessing the impact of alternatives with the objective to select the most suitable technologies. Adamides [19] reviews the technology involved in RBM and discusses the qualitative and quantitative performance characteristics of its coordination mechanism. Agile technological requirements are discussed under hardware that include equipments and tools, and information technologies which include computers and software.

*2.2.2.1. Hardware – equipments and tools.* Agile manufacturing requires 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. The division of assembly, feeding, and unloading tasks between multiple robots should be examined with prioritization based upon assembly time. Rapid software changeover will be facilitated by a real-time, object-oriented software environment utilizing graphical simulations for off-line software development. 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. [35] discussed a design for AM workcells intended for light mechanical assembly of products made from similar components (i.e., parts families).

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 there is a need for effective automated visual inspection systems in AM environments [30]. Agile manufacturing requires agile-enabling technologies such as virtual machine tools, flexible fixturing, and agile design alternatives [29]. As noted 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 [27].

An agile workcell has been proposed 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 singulate the parts and machine vision to locate them. Specialized hardware will be encapsulated on modular grippers and modular worktables that can be quickly interchanged for assembly of different products [33]. Towards achieving agility in manufacturing, Lee [31] has discussed the reconfigurability of a manufacturing system. It is analyzed based on the relationship of 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.

*2.2.2.2. Information technologies.* 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 agility in manufacturing. Therefore, Virtual Reality Software (VRS) for robotics and manufacturing cells simulation can be employed to obtain a 3D graphics model for manufacturing lines. A 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 [34]. As indicated earlier, virtual enter-

prises require high level communication systems including Internet, Multimedia and CAD/CAM to eliminate non-value adding activities in the supply chain. Also, this helps to avoid human related errors in exchanging information and controlling various production and operations in AM environments. Agile manufacturing demands knowledge workers such as computer operators, design engineers, software engineers, systems analysts and corporate planner. Therefore, there is a need to identify the type and level of skills required in AM environments.

Merat et al. [33] have proposed an agile workcell for light mechanical assembly. Object-oriented software (C++) running under VxWorks, a real-time operating system, can be used for workcell control. In this way, agile software architecture was developed for rapid introduction of new assemblies through code re-use. Incorporated in the software architecture is a capability for simulation of the workcell so that controller software could be written and tested off-line, enabling the rapid introduction of new products which facilitates agility in manufacturing. Global access to people, data, software, documents, and multimedia has 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 [32].

The need to rapidly reconfigure an AMS 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. To facilitate testing of AM software, a 3D graphical simulator can be used. It permits workcell control software to be tested with a virtual workcell, which exhibits much of the behavior of the real workcell. Considerable time and effort can be saved by simulating various workcell scenarios, some of which are difficult to create in a real workcell, for example device failure [39].

Yang [38] proposed an object-oriented model of an AMS with a definition of the agile objects at four levels and their features. Meanwhile, 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 agile system by sending information to each other and by accepting information selectively. Here the object-oriented method is adopted to clarify that the agile system is a flat dynamic network in structure, and that in working mechanisms it mainly adapts to the quick market changes by rapid reengineering. The principles of AM can be used to demonstrate the feasibility of customized spaceframe vehicle manufacture using robotic cellular manufacturing. The concepts used can be validated using computer-aided simulation and a full scale manufacturing cell. However, further works need to be done in this respect. Areas of investigation should include system design, joining technologies, tooling design and manufacturing control systems [40].

Bocks [36] developed a Data Management Framework (DMF) to support agility in manufacturing. A DMF can be defined as the ability of an enterprise to manage and distributed data, information, and knowledge as the decisive enabler for core enterprise business process. The purpose of DMF is to provide a seamless enterprise data management solution in support of the AM environments. Integration of current fragmented computer systems, causing over-complexity, is perhaps the biggest challenge the AM enterprise faces.

Wang et al. [37] present an Internet assisted manufacturing system for AM practice. This system uses 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 (FMS), 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.

From the review of agile-enabling technologies, it can be easily noted that the selection of technologies for achieving agility in manufacturing depends upon the strategies that are selected to meet chang-

ing market requirements. For example, JIT may require EDI and FMS needs AGVs, Robots, and NC machine tools. Nevertheless, agility heavily relies on virtual manufacturing/enterprise or physically distributed manufacturing environments. Therefore, technologies such as IT, manufacturing cells, robots, flexible part feeders, modular assembly hardware, automated visual inspection system, virtual machine tools, flexible fixturing, CAD/CAM and automated high-level process planning are essential for developing AMs.

### 2.2.3. Systems

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, an attempt has been made in this section to 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.

*2.2.3.1. Design systems.* Agile manufacturing requires rapid product design systems with the objective to switch over to new products as quickly as possible. This in turn needs a system to group various resources and products with the objective to reduce the non-value adding activities and hence the time to reach markets with right products at the right time. Candadai et al. [43] 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.

Monsplaisir [50] describes the evaluation of two Computer Supported Cooperative Work (CSCW) prototypes to aid engineering teams in the design of an AM facility. The CSCWs facilitated consideration of a large number of flexibility and agility criteria associated with the design of manufacturing systems. Both prototypes support the functions such as anonymous inputs, parallel processing of information, group memory, electronic brainstorming, and consensus building. One of the two CSCW prototypes included three enhancements to further improve consensus building in the design teams. The laboratory test results indicate that both CSCW prototypes provided effective support for design teams.

As discussed earlier, both hardware and software reconfigurability are required to achieve agility in manufacturing. Kusiak and He [25] developed three 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 markets, CE principles can be employed in product development process in AM enterprise.

#### 2.2.3.2. *Production planning and control systems.*

For virtual companies, traditional production control and management systems, methods and theories do not satisfy their needs for production planning and control. The following aspects are to be considered for PPC in AM environments: (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 a virtual company; (3) a flexible or dynamic company control structure to cope with uncertainties in the market; (4) adaptive production scheduling structure and algorithms to cope with uncertainties of production state in virtual company; (5) modelling of production states and control system in a virtual company; and (6) the reference architecture for a virtual company [16].

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 unreli-

able or difficult to maintain. This requires designing the software specifically to facilitate future changes. Kim et al. [49] have developed a software architecture for control of an AM workcell, and demonstrated its flexibility with rapid changeover and introduction of new products. AMSs can benefit significantly from a database support for partner selection, and mistake proofing.

Lee et al. [51] describe an AM Database System (AMDS) designed for capturing and manipulating the operational data of a manufacturing cell. AMDS is a continuous data gathering, real-time Data Base Management System (DBMS), and it can be logged either locally or remotely and used for off-line analysis as well. The temporal operational data obtained can be used for performance and reliability analysis, high-level summary report generation, real-time monitoring and active interaction.

Song and Nagi [15] propose 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 World Wide Web based on a client-server architecture. Systems such as ERP, EDI and EC can be employed for operations control activities of AM enterprises after making appropriate modifications to those systems with the objective to incorporate the system specific characteristics of AM.

#### 2.2.3.3. *Data management and system integration.*

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 must be able to be reconfigured in a very short time and should be able to include parts of information systems from other companies if a Virtual Corporation is

required to meet the market demand. The traditional, common shared data base model of integration has severe problems in this environment. The Systems Integration Architecture (SIA) 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 should allow for the integration of functions and control as well as data [14].

Rapid software changeover can be facilitated by the use of a real-time, object-oriented software environment, modular software, graphical simulations for off-line software development, and an innovative dual VME (Virtual Manufacturing Enterprise) bus controller architecture. These agile features permit new products to be introduced with minimal downtime and system reconfiguration [55]. 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 [24].

McMullen [54] shows how the philosophies, practices, decision processes, measurements, logistics, and systems architectures of 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 major issues that should be resolved, namely what sort of performance measures would be 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 for the optimal selection of partners in agile supply chain with help of information analysis tools like Quality Function Deployment (QFD).

Most of the available systems are developed for traditional manufacturing environments where a static market behavior and resources have been employed for producing goods and services. For physically distributed manufacturing environments, systems such as ERP would be more suitable. The support systems for AM heavily rely on computer-based information systems including EDI, Internet and Electronic Commerce. Therefore, a flexible architecture for systems to accommodate temporary alliances will help to improve enterprise integration and hence agility in organizations.

#### 2.2.4. People

This section reviews the literature on human factors in AM environments. The demands that AM initiatives will place on the current and emerging work force to achieve increasing levels of quality and flexibility with lower costs and shorter product life cycles are discussed in this section. The issues of worker selection, continuous skill development, work place design, equipment maintenance, process improvement, mistake proofing, and process reconfiguration for new products are to be considered from the perspective of workforce required for the development of AMSs [57]. The following key issues of human factors are to be considered in agile environment: knowledge workers, multilingual workforce, multinational workforce, incentive schemes, type and level of education and training, relation with unions, and pay award.

*2.2.4.1. Knowledge workers.* Agile manufacturing can be operated effectively with the help of knowledge workers such as computer operators, draftsman, design engineers and maintenance engineer. Since AM is of more IT-intensive, there is a need to improve the productivity of knowledge workers with the objective to achieve agility in manufacturing. 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 [56] briefly summarizes human factors contributions to: (1) development of agile business practices; (2) design of enabling technologies; and (3) management of the introduction and fielding of new technologies and business practices. The author also discussed human factors related to the communications and information infrastructure essential to an organization making the transition from traditional to agile product development. Also, knowledge workers should be flexible taking into account the responsibility of multiple tasks and communicating in multi-lingual in a physically distributed environment of AM enterprise.

*2.2.4.2. Top management support and employee empowerment.* Gunasekaran [17] highlights the role of employee empowerment in improving the co-operative supported work in a physically distributed VE enterprises. Achieving agility in manufacturing requires radical changes in the line of reengineering business process. This level of change in any organization demands a total support of top management in terms of providing necessary technical and financial support together with employee empowerment. As part of a 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 the product development project structure and the facilitation of information flow in a large, geographically dispersed, project team. This responsibility should reflect a recognition of the importance of human interactions in an information-driven product development process [59]. Also, top management involvement is vital to effective re-engineering of the supply chain and logistics in agile environments [21]. There is not much discussion in the literature concerning the top management support and level of involvement in the design and implementation of AMSs.

*2.2.4.3. Training and education.* It is not clear yet what sort of training and education required to motivate the employees to take part in the develop-

ment of AM. This section spells out some of major training and education requirements in AM environments.

Agile manufacturing has different requirements of workforce as compared to that of 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 favor employees responsible for a particular product, part or process [60]. These to some extent define the characteristics of agile workforce and the training and education required and some of them are: IT-skilled workers, knowledge in team working and negotiation and advanced manufacturing strategies and technologies, empowered employees, multifunctional workforce, multi-lingual workforce, and self-directed teams [9,44,56,59]. In a VE, the nature of training and education should have a different focus as compared to 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 computerised information analysis and synthesis.

The literature available on AM workforce is rather limited [17]. 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 deal with enabling technologies and some strategies of AM. However, human factors play a significant role in the successful development and implementation of AM.

### **3. Comments on agile manufacturing literature and future research directions**

Theoretically derived hypotheses and empirical studies to test them are conspicuously absent from

studies of the agile organization. A study by Hoyt et al. [62] a scene in this direction. Although it seems intuitive that the ability to respond to dynamic and unpredictable changes in the environment should contribute to a company's success, this fact has not been scientifically tested.

The survey of literature has provided further insights into the AM concepts and systems including strategies, technologies, systems and people. From the analysis of AM literature, the following are some of the future research directions that would assist in achieving agility in manufacturing more effectively [17].

- (i) A methodology for evaluating potential partners for agile enterprises based on core-competencies and market forces needs to be developed. Criteria for selecting partners of agile enterprise should be identified with the help of suitable conceptual and empirical research.
- (ii) A framework for determining the type and level of different skills required for agile enterprise should be developed using multiple site case studies. Furthermore, the nature of training and education required for workforce should be precisely defined taking into account the geographically dispersed partners in AM environments. Suitable information systems need to be developed for determining the type of skills and numbers of workers required in agile environments.
- (iii) The infrastructure and organizational characteristics of agile enterprise can be determined by developing a suitable theoretical framework and testing them with real life manufacturing environments. This framework essentially centers around the nature of information and material flows in AM enterprise. The issues of temporary alliances based on core competencies are to be embedded in the proposed empirical studies.
- (iv) In agile enterprises, supply chain links are often temporary and hence flexible. Therefore, there is need to develop suitable performance measurements and investment justification techniques for this environment.

- (v) An investigation on the selection of suitable architectures for agile enterprises would offer further insights into the design of AMSs. Also, appropriate capacity planning and scheduling methods are to be devised to support the effective operations of physically distributed virtual enterprises in AM environments.
- (vi) In a physically distributed agile enterprise environment, there is a need for a different quality management system. All the modern quality management strategies and methods can be used for agile environments, but need to be modified taking into account the reconfigurability and dynamics of agile organizations.
- (vii) The cost accounting systems such as Activity-Based Costing (ABC) would be suitable for advanced manufacturing environments. However, considering the characteristics of agile enterprise, the application of ABC needs further investigation. Physically distributed manufacturing environment demands a simple cost accounting system to overcome the difficulties of communication, integration and domestic regulations among geographically dispersed partners.
- (viii) Gaining rapid response to changing customer demand requires equally agile logistics. Logistics can be helped by appropriate product design and tooling to ease materials handling. Fewer stock lines and greater interchangeability of items reduce the working capital and the risk of obsolescence of slow moving lines [21]. The issue of logistics in AM environments has not received significant attention from researchers. For example, what sort of systems would be suitable for purchasing and distribution of goods would be appropriate in AM environments which include VE based on temporary alliances need to be investigated further.

Realizing the importance of a framework for developing AMSs, an attempt has been made in this paper to develop a framework for AM based on the literature survey and other reported case experiences.

#### 4. A framework for the design of agile manufacturing systems

In this section, a framework for the design of AMSs is developed. This development is based on the literature survey and its analysis. It can be seen that most of the literature on AM and related issues either deal with strategies or techniques, but not an integrated view of developing an AMS. In this section, an attempt has been made to present an integrated strategic and techniques framework for the design and development of AMSs together with people and systems issues. Agile manufacturing can successfully be accomplished using various well-defined agile system architectures. The system architecture for AM may include control, function, process, information, communication, distribution, development, and implementation [46].

Effective and efficient implementation of AMSs require enterprise level integration. The first step in this direction is to integrate design, process planning and scheduling. A bidding-based approach to the integration of computer-aided design, process planning and real time scheduling can be used for the design and implementation of AMS [63]. The product is represented in a STEP model with detailed design and administrative information including design specifications, batch size, and due dates. Upon arrival at the manufacturing facility, the product is registered in the shop floor manager which is essentially a coordinating agent. The shop floor manager broadcasts the product's requirements to the machines. The shop contains autonomous machines that have knowledge about their functionality, capabilities, tooling and schedules. Each machine has its own process planner and responds to the product's request in a way that is consistent with its capabilities and capacities. When more than one machine offers certain process(es) for the same requirements, they enter into negotiation. Based on processing time, due date and cost, one of the machines wins the contract. The successful machine updates its schedule and advises the product to request raw material for processing. The concept was implemented using a multi-agent system in an object-oriented programming language. The task of decomposition and planning are achieved through contract nets

[63]. As discussed earlier, Internet plays a significant role in AMSs.

Based on the literature survey, a conceptual model for the development of AMSs is developed as shown in Fig. 1. As indicated earlier, the model has been developed along four key dimensions including strategies, technology, people and systems. The main objective here is to develop an integrated AMSs with the help of suitable strategies and techniques to develop rapid partnership formation, VE and reconfigurability for mass customization. Further details of the model are discussed hereunder.

##### 4.1. Strategies

Long-term decisions considering the reconfigurability of the organization with the objective to compete in the global market by mass customization are important to make use of various resources available for producing quality goods and services. The following are some of the strategic decision areas that should be considered while developing AMSs: CE, rapid partnership formation, strategic alliances, virtual enterprise, physically distributed manufacturing systems [17].

Partner selection is one of the most important activities in agile enterprise. Selecting manufacturing partners in AM is an endeavour that is worried with the complexity and dynamic of the market driven by customer needs as well as the inherent subjectivity of the selection process. Traditional vendor selection methodologies do not lend themselves as a ready solution to these needs of agile environment [11]. The criteria for selecting partners are not only based on the cost and responsiveness, but should also be based on the quality of goods and services, location of the company, IT skills, and the effectiveness of their supply chain including the flexibility. For instance, CE can be used for new product developments and partner selection based on core competencies.

The increased customization, and the subsequent adoption of CE practices driven by the significance of the product time-to-market and compounded by the distributed nature of enterprises, makes it very difficult to accurately estimate the product manufacturing cost and the cycle time for new products.

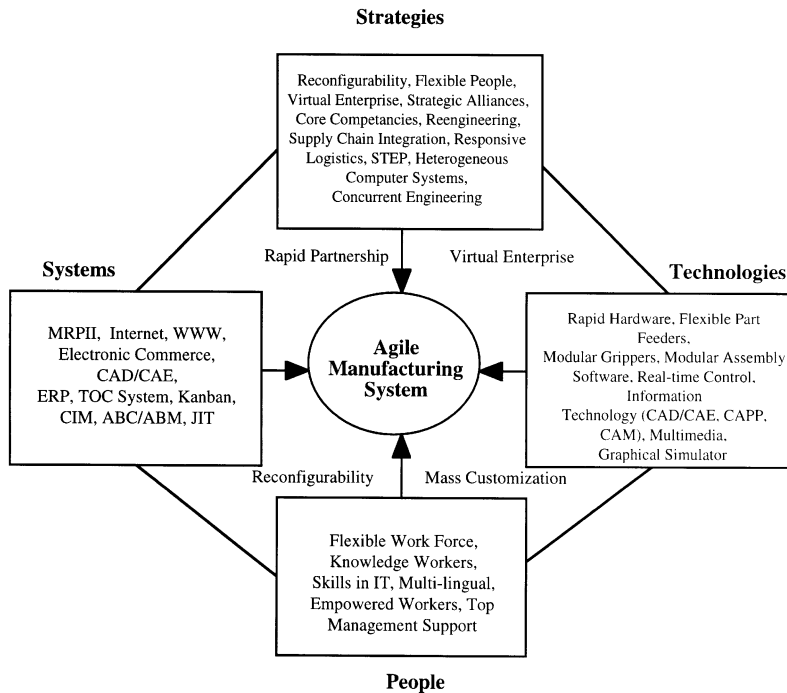


Fig. 1. Development of an agile manufacturing system.

Appropriate cost accounting practices and performance measures should be adopted in AM environments. It is not simply based on non-financial performance measures, but also financial performance measures. For example, the partner's performance can be measured by the time to deliver the product and of course the cost as well. The intangible factors are significant in AM environments and are difficult to quantify, such as the in-house information and communication systems. Therefore, there is a need to identify and measure intangibles in agile enterprises [20].

In AM environments, 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 certain product are important. A decision support system for design evaluation and partner selection in AM needs to be developed. Therefore, every company must find the right combination of culture, business practices, and technology that are necessary to achieve agility in its organization. After analyzing the strategic options of AM, the

strategies such as market forces, partnership formation, VE, rapid product developments are the key strategies to achieve agility in manufacturing.

#### 4.2. Technology

As discussed earlier, strategies of AM with suitably supported technologies would enhance the success of achieving/improving agility in organizations. Therefore, key technologies to achieve agility based on the strategies selected are highlighted here. In AMSs, rapid hardware changeover can be made possible by robots, flexible part feeders, flexible fixturing, modular grippers and modular assembly hardware. The flexible feeders rely on belt feeding and binary computer vision for pose estimation. This has a distinct advantage over non-flexible feeding schemes such as bowl feeders which require considerable adjustment to changeover from one part to another [55].

The agile-enabling technologies such as Internet, Multimedia, EDI, Electronic Commerce, flexible

manufacturing cells, Robotics and CAD/CAM need to be suitably incorporated within the scope of the VE to achieve agility in manufacturing.

#### 4.3. *Systems*

In the AM paradigm, where multiple firms cooperate under flexible virtual enterprise structures, there exists a great need for a mechanism to manage and control information flow among collaborating partners. In response to this pressing need, an AM information system integrating manufacturing databases dispersed at various partner sites needs to be developed.

Agile manufacturing requires agile support systems which can be obtained by computer-aided information systems for planning and control activities of manufacturing. Systems such as MRP, ERP, and CAD/CAM and KBS can be used to collect information and make appropriate decisions concerning the effective operations that would support agility in manufacturing organizations. The reason why computerized information systems are recommended for AM is due to the characteristics such as VE, rapid prototyping and physically distributed manufacturing systems.

There is a need for the development and integration of information infrastructure to facilitate distributed design, planning, manufacturing, and marketing functions in agile enterprise. The purpose of this is to achieve multipath agility in the product development process. Multipath agility provides increased access to alternative resources and information, and achieves improvements in productivity and quality through flexibility of access and utilization of resources, rather than through stepwise improvements in any one task. These concepts will be tested through demonstration case studies in many-to-one and one-to-many design-manufacturing cycles of real products [42]. Nevertheless, integration of current fragmented computer systems, causing over-complexity, is perhaps the biggest challenge the AM enterprise faces [36].

Partner organizations may remain competitive in some markets or return to a competitive relationship with other partners after the dissolution of the VE. Sensitive information and business pro-

cesses 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 [17].

To make a transition to the agile industry, where manufacturing firms cooperate under virtual enterprise structures, there is a need to develop mechanisms for agile partners to cooperate flexibly and dynamically. An individual partner, with its information system, can plug in (out) of the VE supported by a communication network such as the Internet. It is through the integration of these partner information systems that information management is possible in collaborative activities. The conceptual information system for an agile manufacturer consists of two hierarchies, viz. the information hierarchy and the transaction hierarchy. The information hierarchy represents agile information using Object Oriented Methodology (OOM), and the transaction hierarchy models partner transaction management using a Knowledge Based Systems (KBS) accommodating expert rules. Using the Client-Server architecture, an integrated partner information system for improving flexibly and dynamically can be developed [15].

In agile enterprise where manufacturing partners share product related data to come up with new, customized, and high quality products at minimal leadtimes. The principles of group technology (GT) can be used. The information on product design is assumed to be available in the product databases of distributed partners, and can be generated through an existing GT design processor. A software system using object-oriented technology will be useful in implementing the procedure [48]. Agile manufacturing systems can benefit significantly from a database support. An AM database system (AMDS) designed for capturing and manipulating the operational data of a manufacturing cell will be helpful.

Design for agile assembly is accomplished by considering operational issues of assembly systems at the early product design stage. The flexibility required of an AMS must be achieved largely 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 [25].

Agile manufacturing can be successfully accomplished using various well-defined system architectures. For example, Jung et al. [46] provide a primary sketch of architectural requirements for rapid development of AMSs. This architecture can include control, function, process, information, communication, distribution, development, and implementation.

#### 4.4. People

The most critical problem in agile environment is how to manage and motivate workforce to support the flexibility and responsiveness. Forsythe [56] discusses the human factors in AM. For the development of agile business practices, there needs to be consideration of human factors affecting decision making within fast-paced dynamic environments [58]. When information does not flow, due to technical or human issues, agility is lost. For this reason, elimination of human points of failure in infrastructure support is essential [59]. If users are unwilling or reluctant to accept agile practices and enabling technologies, AM will fail from the inability to overcome the inertia of traditional, often deeply ingrained practices. Agile manufacturing poses threat to the comfort of managers due to the empowerment of product development teams and the increased openness of information.

Concurrent engineering within a fast-paced product development environment favors collaborative work between engineering disciplines. Most of the challenges of human factors posed by the agile environment can be overcome by a series of team meetings during which the team jointly developed 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. To overcome these factors, two strategies

can be adopted: (i) various mechanisms can be employed to allow team members to meet face-to-face and establish personal familiarity (e.g. team training and project planning), and (ii) to sustain familiarity throughout the course of the project (through monthly all-hand meetings, weekly lunches, social events).

Information may be transmitted via multiple channels depending on urgency, content and distribution through phone, voice-mail, fax, e-mail, and http [56]. The agile workforce should be capable of meeting increasing technological challenges, designing their work places, solving quality-related problems and team-to-team learning, improving equipment availability, using mistake-proofing processes, dealing with increased complexity, and finally, helping labor unions harmonise their members and company expectations [57].

## 5. Summary and conclusions

With the rapid changes taking place in the global market, it becomes clear that enterprises working on an AM base or in mass customization will rapidly become leaders. In order to design efficient production systems and factories operating in these manufacturing paradigms, new design approaches need to be developed. This paper synthesizes some of the research work done on the AM to develop a framework for the development of AMSs. The model presented in this paper can be tested with the help of suitable empirical and multiple case studies. Also, classical organization theory and strategy research methods are useful for the characterization of AM organizations. The subject of AM needs more feasibility studies from the perspectives of establishing VE, temporary alliances and their implications on the relationship with labor unions and jurisdictions. The following are some of the major issues that could be considered by researchers and practitioners when developing AMSs:

- (i) The relationship between competitive basis such as flexibility, quality, productivity, responsiveness, and cost needs to be investigated in relation to agility in manufacturing.

- (ii) Knowledge management is a crucial issue in a VE enterprise and therefore, a framework should be developed for the effective management of knowledge in AM enterprises.
- (iii) There are not many studies on the application of operations research models for the design and development of AM. However, suitable models need to be developed for the purpose of making decisions in a virtual and physically distributed manufacturing environment.
- (iv) The workforce characteristics in AM need to be defined more precisely with the help of appropriate empirical and case study research.

The following are the summary of issues that should be addressed in agile manufacturing as compared to traditional advanced manufacturing systems: (i) the implications of temporary alliances on the enterprise communication and co-ordination, (ii) the influence of virtual enterprise and physically distributed manufacturing on the human relations management, and (iii) the technologies and human skills required for the information intensive manufacturing environment.

## Acknowledgements

The author is most grateful to two anonymous referees for their helpful comments on the earlier version of the manuscript which helped to improve the presentation of the paper considerably.

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