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A review of agile manufacturing systems

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About a decade ago, the agile manufacturing paradigm was formulated in response to the constantly changing 'new economy' and as a basis for returning to global competitiveness. While agility means different things to different enterprises under different contexts, the following elements capture its essential concept: agility is characterized by cooperativeness and synergism (possibly resulting in virtual corporations), by a strategic vision that enables thriving in face of continuous and unpredictable change, by the responsive creation and delivery of customer-valued, high quality and mass customized goods/services, by nimble organization structures of a knowledgeable and empowered workforce, and facilitated by an information infrastructure that links constituent partners in a unified electronic network. During this period, a significant amount of attention from both the academic and industrial communities has produced a large body of results in research and development related to this topic. Each contribution has tackled a different aspect of this large field. In this paper, we review a wide range of recent literature on agile manufacturing. About 73 papers from premier scientific journals and conferences have been reviewed, and a classification scheme to organize these is proposed. We critique these bodies of work and suggest directions for additional research and identify topics where fruitful opportunities exist.

1. Introduction

World-class performance is a moving target that requires constant attention and effort; the process is a neverending journey. In the past, economies of scale ruled the manufacturing world and everybody knew that mass production and full utilization of plant capacity was the way to make money. This style of manufacturing, resulted in inflexible plants that could not be easily reconfigured, and were associated with swollen raw materials, work-in-process and finished goods inventories.

Since the early 1980s, in pursuit of greater flexibility, elimination of excess in inventory, shortened lead-times, and advanced levels of quality in both products and customer service, industry analysts have popularized the terms 'world-class manufacturing' and 'lean production' (Sheridan 1993).

In the 1990s, industry leaders were trying to formulate a new paradigm for successful manufacturing enterprises in the 21st century; even though many manufacturing firms were still struggling to implement lean production concepts.

In 1991, a group of more than 150 industry executives participated in a study. Their efforts culminated in a two-volume report titled '21st Century Manufacturing Enterprise Strategy', which describes how US industrial competitiveness will—or might—evolve during the next 15 years. As a result, the Agile Manufacturing

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Enterprise Forum (AMEF), affiliated with the Iacocca Institute at Lehigh University, was formed and the concept of agile manufacturing was introduced (Sheridan 1993, Struebing 1995, Richards 1996, Nagel and Dove 1991).

For many, 'Lean manufacturing' and 'Agile manufacturing' sound similar, but they are different. Lean manufacturing is a response to competitive pressures with limited resources. Agile manufacturing, on the other hand, is a response to complexity brought about by constant change. Lean is a collection of operational techniques focused on productive use of resources. Agility is an overall strategy focused on thriving in an unpredictable environment. Focusing on the individual customer, agile competition has evolved from the unilateral producer-centred customer-responsive companies inspired by the lean manufacturing refinement of mass production to interactive producer-customer relationships (Goldman *et al*., 1994). In a similar sense, some researchers contrast flexible manufacturing systems (FMS) and agile manufacturing systems (AMS) according to the type of adaptation: FMS is reactive adaptation, while AMS is proactive adaptation.

Agility enables enterprises to thrive in an environment of continuous and unanticipated change (Richards 1996). It is a new, post-mass-production system for the creation and distribution of goods and services. Agile manufacturing requires resources that are beyond the reach of a single company. Sharing resources and technologies among companies becomes necessary. The competitive ability of an enterprise depends on its ability to establish proper relationships, and thus cooperation seems to be the key to possibly complementary relationships. An agile enterprise has the organizational flexibility to adopt for each project the managerial vehicle that will yield the greatest competitive advantage. Sometimes this will take the form of an internal cross-functional team with participation from suppliers and customers. Sometimes it will take the form of collaborative ventures with other companies, and sometimes it will take the form of a virtual company (Nagel and Dove 1991).

Agile manufacturing is attracting an increasing amount of attention from both the academic and industrial communities. Extensive programmes are being conducted on relevant issues to propagate agile manufacturing concepts, to build agile enterprise prototypes, and eventually to realize an agile industry. The AMEF has sponsored several major conferences and has created at least 18 ongoing 'focus groups' to explore further various aspects of agility and the infrastructure needed to support them. Considering the relevance of agile manufacturing we believe that new fruitful opportunities can be identified. The objective of this paper is to review a wide range of existing literature on agile manufacturing systems, to propose a classification scheme for those papers, and to identify areas where further research is needed.

2. Classification scheme for agile manufacturing research

Table 1 illustrates the classification scheme for the survey on agile manufacturing systems. Nine major categories are defined and the frequency of the citations in each category is identified. Information systems was attributed the largest number of citations (21), followed by supply chain (13). Product and manufacturing systems design, and business practices and processes had the same number of citations (9 each). The next research area with the largest frequency was facilities design and location (8).

The search process was focused on articles from three different sources. We used electronic databases of abstracts, reviewed the sources cited within the articles, and

Research topic	Research subtopics	No of citations
Product and manufacturing systems design		9
Process planning		5
Production planning, scheduling and control		4
Facilities design and location	Facilities design	5
	Facilities location	3
Material handling and storage systems		1
Information systems	Integrated information systems	4
	Information systems designed for supporting specific areas	10
	Architectures: requirements and implications	4
	Information exchange	2
	Evaluation of information models	1
Supply chain	Strategies	4
	Partner selection	9
Human factors		3
Business practices and processes	Progress evaluation in several countries	4
	Business issues	5
Total		73

Table 1. Classification scheme for agile manufacturing.

browsed through first tier journals and conference proceedings. We disregarded references for which full text was unavailable. In addition, we refer the reader to focused journals such as the *International Journal of Agile Management Systems*, the *International Journal of Agile Manufacturing*. A total of 73 citations on agile manufacturing were reviewed (see tables 1 and 2). Table 2 provides the sources. The majority of the citations were found in journals (56.2%), while proceedings, conferences, and others contributed to the remainder (43.8%). Three journals and one proceedings, *International Journal of Production Research, IIE Transactions, International Journal of Production Economics*, and *IERC Proceedings 1997*, accounted for 42.5% of the citations.

Table 3 provides a breakdown of the number of citations by research classification and by year of publication. Given that the concept of agile manufacturing was introduced in 1991, our survey begins with papers published during this year. As we can see, agile manufacturing is a recent research area. The year 1997 was the most productive year because the number of publications represents 30.1% of the total of papers reviewed here. Before 1995, the number of papers was scarce (9.6%). In 1995 a notable increase occurred in the number of papers published. Thereafter, the number has been maintained, with the exception of the prolific 1997 as we noted previously. For each one of the four research topics with the greatest number of citations, a sub-classification was performed (see table 1).

Source	No. of citations
19th IIE Systems Integration Conference	1
Communications of the ACM	1
Computers and Industrial Engineering. (International Conferences)	5
Computers and Operations Research	1
Computers in Engineering. 14th ASME. ICE Conference and Exposition	1
Computers in Industry	1
Concurrent Product and Process Engineering. ASME	1
Concurrent Product Design. ASME. IME Congress and Exposition	1
Decision Support Systems	1
Engineering Data Management & Emerging Technologies. ASME. IME Congress and Exposition	1
Ergonomics in Design	1
Human Factors and Ergonomics in Manufacturing	2
IEEE Software	1
INRIA/IEEE Symposium on Emerging Technologies & Factory Automation. Proceedings	1
IERC Proceedings 1995	4
IERC Proceedings 1996	4
IERC Proceedings 1997	6
IERC Proceedings 1998	1
IIE Transactions	9
International Journal of Advanced Manufacturing	1
International Journal of Human Factors in Manufacturing	1
Internationa Journal of Operations and Production Management	1
International Journal of Production Economics	7
International Journal of Production Research	9
ISR University of Maryland	1
Journal of Engineering Manufacture	1
Journal of Manufacturing Systems	1
Journal of Materials Processing Technology	2
Manufacturing Science and Engineering. Congress (1995, 1994)	2
Production	1
SORCIIER, University Laval	1
SUNY at Buffalo, Department of Industrial Engineering	2
Total	73

Table 2. Summary of journals on agile manufacturing.

3. Agile manufacturing research

Agile manufacturing as a new strategy is captivating the attention of researchers. A growing amount of research has arisen. Using the classification scheme developed in the previous section, research findings in each major category will be reviewed in the subsequent subsections.

3.1. *Product and manufacturing systems design*

Product and manufacturing systems design is the first major category identified in the survey. A number of papers on this area have been published. Our review found nine papers devoted to this category. Table 4 shows the areas analysed for each paper. Seven papers made contributions to design of products. Three out of seven not only talk about design of products but present findings about design of manufacturing systems. In addition, two of the previous three analysed the integrated

Research topic	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Product and manufacturing systems design	0	0	0	2	2	0	3	2	0	0
Process planning	0	0	0	1	0	0	3	1	0	0
Production planning, scheduling and control	0	0	0	0	0	1	2	0	1	0
Facilities design and location	1	1	1	0	0	1	3	0	1	0
Material handling and storage systems	0	0	0	0	0	0	1	0	0	0
Information systems	0	0	0	1	3	5	6	5	1	0
Supply chain	0	0	0	0	3	2	0	2	5	1
Human factors	0	0	0	0	0	1	2	0	0	0
Business practices and processes	0	0	0	0	1	2	2	1	3	0
Total	1	1	1	4	9	12	22	11	11	1

Table 3. Citations by year and topic.

	Areas		
Author	Design of products	Design of manufacturing systems	Integrated design
Lee (1998)	Yes	Yes	Yes
He and Kusiak (1995)	Design for scheduling	No	No
Kusiak and He (1997)	Design for assembly	No	No
Cheng *et al.* (1998)	Yes	No	No
Lee (1997)	Design for reconfigurability	Design for reconfigurability	Yes
He and Kusiak (1994)	Design for assembly	Yes	No
Quiinn *et al.* (1997)	No	Design of manufacturing work-cell	No
Kusiak and Feng (1994)	Yes	No	No
Dove (1995)	No	Yes	No

Table 4. Areas analysed for each paper.

design of components and manufacturing systems. A brief description of the nine articles is presented in the following. Lee (1998) considers agile manufacturing in the early design of components and manufacturing systems. A design rule for agility is formulated, and substantiated by numerical results. 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. A machine relocation problem is mathematically formulated and solved with a solution procedure developed. This work was oriented for products with short manufacturing lead times. This design rule has limitations in obtaining standard cost and time of machine relocations, due to a lack of auxiliary devices, guidelines and references for relocating machines.

He and Kusiak (1995) use the delayed product differentiation in their work as a powerful design concept that can be used to achieve agility. Delayed product differentiation refers to delaying the time when a product assumes its identity. Increasing the level of part commonality at early stages of the manufacturing process can delay the differentiation of products. The delayed product differentiation concept is cited as an assembly-driven strategy by other authors. He and Kusiak (1995) discuss the implementation of a delayed product differentiation strategy in a manufacturing system. The problem of selecting the designs so as to minimize the number of parts and the manufacturing cycle time is formulated and solved. Their strategy uses graph representation of the structure of the product, which is classified into three classes according to the assembly level of each part and the highest assembly level. After that, a selection of differential design applying two design rules is developed. Finally, an integer programming formulation of the problem is developed in order to obtain the optimal design. The paper does not define boundaries or stopping rules for the number of designs to develop before the selection process is applied. In addition, no collective impact of multiple product designs is considered.

Kusiak and He (1997) propose three rules applicable to the design of products for agile assembly from an operational perspective. The first rule is to design a product to satisfy the manufacturing operations requirements. A printed circuit board design example was used to illustrate this rule. The second rule is to simplify through the design of products their flow in a multi-product assembly system. This rule suggests that, in order to avoid backtracking in a multi-product assembly line, products should be designed so that cycles in a superimposed assembly graph are eliminated. The third rule is to design a new product for a compatible production schedule. Illustrative examples are provided to demonstrate the potential. Procedures and algorithms for implementing each one of these design rules are presented. The trade-off analysis associated with each design rule was discussed. The proposed rules are intended to support the design of products for meeting the requirements of agile manufacturing. Design for agile assembly is accomplished by considering operational issues of assembly systems at the early product design stage. The rules proposed consider operational issues during the design process.

Cheng *et al* (1998) present a new approach for implementation of agile design and manufacturing concepts. The approach is based on the integration of artificial intelligence (AI) and internet technologies with conventional design and manufacturing techniques. An architecture based on AI and internet programming (Java) is proposed for remotely and quickly accessing bearing design and manufacturing expertise at low cost and thus implementing design and manufacturing agility. The intelligent bearing design system includes seven modules, such as electronic catalogue, intelligent selection, mounting details, sealing devices, lubrication, manufacturing database and design module. These modules are developed through the integration of AI with the conventional bearing design and manufacturing techniques. A designer can remotely interact with these modules and thus access the bearing design and manufacturing expertise to quickly and effectively solve the prob-

Author	Design rules (number)	Formulation developed	Objective minimize
Lee (1998)	Yes (1)	Integer programming	Overall material handling cost, relocating cost and lost revenue during machine relocations
He and Kusiak (1995)	Yes (2)	Integer programming	The total part count differentiation cost and production cost
Kusiak and He (1997)	Yes (3)	Integer programming	Total placement time, the change in the mean completion time
Cheng *et al.* (1998)	No	No	No
Lee (1997)	Yes (3)	Integer & dynamic programming	Overall reconfiguration cost among systems for each component design
		Integer programming	Total processing cost, the cost of all possible system reconfigurations and the purchase cost of resources
He and Kusiak (1994)	Yes (4)	No	No
Quiinn *et al.* (1997)	No	No	No
Kusiak and Feng (1994)	Yes (10)	No	No
Dove (1995)	Yes (10)	No	No

Table 5. Product and manufacturing systems design. Comparison of papers.

lem. The paper concludes with a discussion on the potential benefits, and the future applications of AI and internet-based agile manufacturing technology in industry. The work developed shows how several users can access one database. However, in an agile manufacturing environment, several users must be able to access several databases. This kind of availability was not developed in this work, nor were consistency issues related to multiuser distributed databases.

Lee (1997) discusses manufacturing system reconfigurability in agile manufacturing. The reconfiguration of a manufacturing system is analysed based on the relationship of component routes, material handling costs, and reconfiguration cost. 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. An algorithm for selection of components and manufacturing resources is developed. This paper was more focused on selection of components than generation of alternative designs. The underlying approach uses similarities of products, but does not mention directions for those products with no similarities.

He and Kusiak (1994) present some insights into the benefits of concurrent design of products and assembly systems, and offer a methodology for design for agile assembly. Four design rules for agile assembly were proposed. Examples were provided to demonstrate the potential of these rules, but no quantitative benefits were provided. The proposed methodology is primarily useful for just-in-time systems.

Author	Heuristic presented
Lee (1998)	Iterative algorithm based on three lemmas and three machine relocation rules proposed by the author
He and Kusiak (1995)	Use of construction algorithm proposed by Kusiak (1990)
Kusiak and He (1997)	Three heuristics were presented, one for each rule. For first rule: swapping components heuristic; for second rule: a graph theory based algorithm for identification of critical pairs of operations in a superimposed assembly graph; for third rule: a compatible design algorithm, whose performance is measured by the change in mean completion time.
Cheng *et al*. (1998)	None
Lee (1997)	Three different formulations were presented, each one solved with different algorithm. The author used the construction algorithm proposed by Kusiak (1990) for the first formulation, LINDO software for the second and for the third an improved algorithm that tries to find components according to the minimum machining cost. It is an iterative process until all resources have been considered.
He and Kusiak (1994)	None
Quiinn *et al*. (1997)	None
Kusiak and Feng (1994)	None
Dove (1995)	None

Table 6. Product and manufacturing systems design. Comparison of papers.

Quiinn *et al*. (1997) successfully validate the critical issues for the design of an agile manufacturing system, which must have a pro-active adaptation. The design of the agile manufacturing work-cell developed in this paper is intended for light mechanical assembly of products made from similar components (i.e. parts families). Flexible parts feeders, machine vision, modular hardware, a sophisticated controller interface, online error correction, graphical simulations and modular software are essential elements of an extensive implementation. The division of tasks between work-cell robots is shown to have a significant effect on assembly times. And using multiple robots in tandem to perform sub-assemblies is shown to be advantageous in a typical assembly task. Concepts for Design for Manufacture and Assembly (DFMA) were developed as guidelines for future products to facilitate automated assembly. These concepts are only valid for light mechanical assemblies.

Kusiak and Feng (1994) investigate the impact of product design on set-up reduction. They classified the set-ups in the two types: inter-lot and in-lot set-ups. The first denotes the term 'set-up' as used in the production planning and control literature. The second was further divided into inter-machine and in-machine set-ups. The inter-lot set-up time (traditional set-up concept) determines the lead-time of a new lot, and the cost of this type of set-up impacts the economic lot size. The inter-machine set-up (a type of in-lot set-up) has an impact on the inter-lot set-up time and cost. The reduction of the in-lot set-up time shortens the cycle time of each item. Therefore, an agile manufacturing environment is achieved by reducing both the inter-lot and in-lot set-up time. According to the classification of set-ups presented, a number of lemmas and corollaries were introduced. These were very useful in developing rules for set-up reduction. These rules were proposed for a feature-based design environment. In order to illustrate the impact of the design rules, two different studies were developed. First, the authors analysed the impact of product design on the set-up cost and production rate, and second the impact of product design on the economic lot size and production cost. The computational results presented in the paper illustrate the impact on product design due to reduction of inter-lot and in-lot set-up cost (time) and the improvement of some other performance measures.

Dove (1995) presents ten agility design principles including various applications. These ten design principles are based on object-oriented concepts augmented with understandings from production and enterprises systems exhibiting high degrees of adaptability. The principles are classified according to three characteristics: reconfigurable, reusable and scalable. No validation of the principles was presented, either qualitative or quantitative.

Contemporary product design is a highly sophisticated process. It requires the involvement of not only design engineers but also personnel from the departments of manufacturing, finance, marketing, and others. The process usually begins with the motive that a new product is needed to meet the requirements of the customers or innovation to create new markets. This step can be seen as the starting point of a virtual company formation. The literature reviewed (see table 5) on this research topic shows how researchers have focused on furnishing guidelines for the process of product design, providing rules, creating algorithms, or using expertise based on the integration of artificial intelligence, internet technologies, conventional design and manufacturing techniques. Nine papers were reviewed. Only four out of these nine developed a mathematical formulation to the problems presented. They used integer

		Range of benefits	
Author	Variable analysed	Min	Max
Lee (1998)	Percentage improvement (reduction) in manufacturing lead time	10.34%	17.7%
	Percentage reduction on total cost (reconfiguration + material handling)	11.91%	68.65%
He and Kusiak (1995)	Change in the makespan of a part	−3.5	9
Kusiak and He (1997)	Percentage reduction of mean completion time	7.20%	7.20%
Cheng *et al.* (1998)	None	–	–
Lee (1997)	Percentage improvement of reconfiguration cost	11.13%*	69.75%*
He and Kusiak (1994)	None	–	–
Quiinn *et al.* (1997)	None	–	–
Kusiak and Feng (1994)	Percentage reduction of setup cost	32.44%	58.76%
	Percentage reduction of setup time	32.47%	58.85%
	Percentage improvement of production rate	31.58%	58.82%
	Percentage reduction of economic lot size	15.45%	43.01%
	Percentage reduction of production cost	10.12%	49.98%
Dove (1995)	None	–	–

*The values provided by the author were 12.53 and 230.53%. He computed the improvement of reconfiguration cost in a non-standard way. He used (OldCost-NewCost)/NewCost.

Table 7. Product and manufacturing systems design. Quantitative benefits presented.

programming or a combination of integer and dynamic programming. Three out of those four papers were interested in cost minimization, while one considered the mean completion time objective. For solving the models, the authors developed heuristics or used previous developments (see table 6). Table 7 shows the quantitative benefits relative to the critical variables of interest that each paper reported. None of them employs data from examples presented by the other authors. The variety in the variables selected to analyse is evident. However most of them used percentages of improvement or change. Each author analysed the output variation of different variables using instances with different variables. The benefits-report shows that large (69.75%) and modest (7.2%) improvements can be achieved. We have to be careful with these comparisons because each author analysed different variables and, also, the manufacturing processes and the data used were entirely different. Further research in this area should be aimed at the development of tools that make possible multiple interaction at the same time, in the same design, and from different partners located around the world. Additional development is also necessary in the integrated design of products and manufacturing systems.

3.2. *Process planning*

Process planning essentially determines how a component will be manufactured. The research done in this area has been focused on the development of new systems (table 8). Manufacturing software systems play a key role in the implementation of process planning for agile manufacturing. However, current software systems are monolithic. They are general and in a closed form. Traditional software development techniques do not cope well with the needs of open systems and, in particular, with rapidly changing requirements, which are crucial for agile manufacturing. Gupta *et al.* (1997) present a generative high level process planning approach for agile manufacturing. The approach requires information about the product design as well as the manufacturing capabilities of potential partners, and consists of two stages: design processing and generation of feasible process alternatives. During design processing, critical design information is extracted from the Standard for Transfer and Exchange of Product model data (STEP) product model. The processes used to manufacture a mechanical product were classified into three types: primary (net-shape process), secondary (material removal process) and tertiary (finishing operations). A two step method: process selection and feasibility assessment was used to generate feasible process alternatives at each level. The approach was implemented in a software system that takes a computer-aided design (CAD) model and outputs a set of feasible manufacturing operations along with candidate manufacturing partners. It is a robust system that can consider components of varying complexity including machined components, forged components, and injection moulded components. Because the approach does not consider detailed component attributes, it can easily model even the most complex components. Under many test cases, the system output is consistent with industrial practice. In an agile manufacturing environment, this approach provides the designer with alternative process plans at an early stage so that the product can be designed to take advantage of partner specific capabilities. In order to compare alternative process plans, the total cost, lead time, and quality indices for each alternative must be determined. The computation of these values was not included in the scope of this paper. It is interesting to note that while other previous works in process planning have been concentrated on a single

Authors	Goal	Approach	Formu-lation	Development of software
Gupta *et al.* (1997)	To develop an automated high-level process planning system.	Generate feasible process alternatives at each level using a two step method: process selection and feasibility assessment. Generative process planning.	No	Yes, use output from CAD model and a set of feasible manufacturing operations along with candidate manufacturing partners.
Iyer and Nagi (1994, 1997)	To develop an automated retrieval and ranking of similar parts system.	Systematic procedure to combine independent similarity indexes to a unique measure for sorting. Variant process planning.	No	Yes, in C and C++ in the UNIX platform. Use modular approach
Olsen and Saetre (1997)	To complete a specification of a product variant for a virtual product.	The virtual product is generated from a generic bill of materials (GBOM) that describes all possible variants of a product. The variability is defined through a set of attributes and attribute values defined by the user.	No	Yes, development of prototype using Gupta's SQL windows development tool.
Feng and Zhang (1998)	To develop a novel architecture for the rapid development of CAPP systems.	Component-based CAPP system integration using prepackaged, plug-compatible software components.	No	Yes, in Visual Basic in a PC in a Microsoft Windows environment. Also an internet-based distributed process planning system architecture was proposed.

Table 8. Process planning. Comparison of papers.

manufacturing process, this paper considered many different types of processes and distributed partners in order to capitalize on the possibilities of agile manufacturing.

Iyer and Nagi (1994, 1997) address the problem of identifying existing parts from the product databases of the collaborating companies that are similar, in one or many characteristics, to a new part at the design stage. The identification of similar products will provide the designer with design characteristics and production histories, and reduce the overall development-time of the new product. The proposed method is based on the principles of group technology (GT), and on the definition of the neighbourhood of similarity of critical design attributes. A two-step approach has been developed for identifying similar parts. The first step is a search and retrieval procedure that acquires and processes the search attributes of the designer and desired level of similarity to generate a list of similar parts from partner product databases. GT codes for the mechanical and electrical attributes of the product are employed in this procedure. The definition of similarity, whole and partial, between the various values of each GT digit has been developed and employed in the similarity search. The second step of the procedure, systematically ranks (sorts) the similar parts by determining a global similarity measure (GSM) based on the search attributes of the designer or overall characteristics. Detailed, critical design information is used to perform feature by feature comparisons using similarity mapping functions to define similarity measures at the feature level. Then, a combination technique, based on analytical hierarchy process concepts, is employed to combine the similarity measures of the various characteristics into a global measure. This is used to sort the list of similar parts so that the most relevant parts based on the preference of the designer can be immediately identified.

A software system implementation using object-oriented technology was developed, which allows the application of the technology through a user-friendly interface. Application of the methods developed in this work is expected to help considerably in variant design, variant process planning, and variant manufacturability evaluation.

Olsen and Saetre (1997) present a new paradigm for customer-oriented production. A system for handling individual product variants is presented. This system can handle a high degree of product variability without demanding redundant structures. The system uses the individual product specifications given by each customer to create a virtual product. The virtual product is generated from a generic bill of materials (GBOM) which describes all possible variants of a product. The variability of each component in the GBOM is defined through a set of attributes and attributes values. The user creates a virtual product, an instance of the GBOM, by specification of these attributes. The virtual product is represented as a data object. This object may be used as a basis for production management. An important feature of this system is its ability to process complete virtual products, i.e. products that are not fully specified. The system is able to generate virtual products that are as yet incomplete. Thus, it is possible to create a virtual product before all specifications are known. A prototype system was implemented.

Feng and Zhang (1998) present a novel integration framework proposed for the rapid development of computer-aided process planning (CAPP) systems for agile manufacturing. The architecture of this new system is built upon the component-based software system concept. The architecture includes: the activity model, the data model, the software component library, the user requirements and software component functions mapping algorithm, the user interface with a scripting capability, the component composition mechanism, and the resource database. The issues for implementing this architecture are discussed. Based on the specifications, an experimental system in Visual Basic was developed and implemented to prove the concept. Additionally, in this study, an internet-based distributed process planning system architecture was proposed and specified as a preview of the next generation of manufacturing planning software architectures. The information infrastructure combines the Internet as software delivery vehicle with the standard for transfer and exchange of product data (STEP) and the common object request broker architecture (CORBA) standard for interoperation of the software components. The authors state that this new system architecture is superior to traditional systems for process planning in a dynamic manufacturing environment. However, they do not quantify the benefits (see table 9).

Products and their components are designed to perform certain functions. The design specifications ensure the performance of these functions. On the other hand, the producers have to use manufacturing processes in order to fabricate components, which will be assembled into the final products. The bridge between design and manufacturing is process planning, translating design specifications into manufacturing process details. Process planning refers to a set of instructions that are used to

Authors	Quantify benefits	Qualitative benefits	Provide examples
Gupta *et al.* (1997)	No	Helpful for selection of partners	Yes, 1 product & 2 different plants
Iyer and Nagi (1994, 1997)	No	Allows to derive detailed similarity with respect to specific features and also compare the results with similar search parameters on other partner databases	Yes, 2 partners & 10 parts each
Olsen and Saetre (1997)	No	Reduction of excessive redundant structures. It has the ability to process completely virtual products, including those still not fully specified	Yes, 1 product
Feng and Zhang (1998)	No	Allows persons to participate in the decision making. Given its modularity it is extendible and adaptable to new applications. It can be extended to other manufacturing planning.	Yes, 2 products. One is a rotational part and the other non-rotational.

Table 9. Process planning. Benefits reported.

make components or parts so that the design specifications are met. Papers analysed in this section developed new frameworks and/or architectures for process planning using different approaches as we can see in table 8. We found two papers that focus on the development of the process planning system. The first generating feasible process alternatives, and the second developing a systematic procedure for identification of parts. Another paper was concerned with the growing customization of products. In this paper a system that can handle a high degree of product variability was developed. The authors of the last paper in this category directed their efforts to an architecture for building CAPP systems, using existing developments (available software). None of the papers developed mathematical formulations but all of them created prototypes for testing their proposals. From table 9, we can see that nobody quantifies the improvements of their proposals. Nevertheless, based in their knowledge and experience the authors say there are benefits using their contributions. Qualitative expected benefits were mentioned.

3.3. *Production planning, scheduling and control*

Production planning, scheduling and control is concerned with manufacturing the right product types, in the right quantities, at the right time, at minimum cost and meeting quality standards. Production planning, scheduling and control are the heart of manufacturing firms. He and Kusiak (1996) developed two models for production planning and scheduling in a virtual corporation. This paper considers that every virtual corporation is formed by a number of manufacturing companies (manufacturing centres) and assembly companies (assembly centres). The first model allocates products to the assembly centres so that the total average set-up and inventory cost is minimized. The model is solved with an efficient heuristic algorithm. The second model deals with scheduling the manufacturing centres. In this paper, the authors assume that each firm has a different production capability (each one can produce different products). Additionally, they assume that partners are manufacturing centres or assembly centres, but not both. This paper also assumes a rotation cycle schedule for the assembly centres. One drawback is that there is no consideration of transportation time separately of the process time.

Don-Taylor (1997) introduces the Design for Global Manufacturing and Assembly (DFGMA) as a tool to assist designers in making optimal sourcing, capital procurement, and market timing decisions in a multi-facility, global environment. More specifically, DFGMA is a mathematical tool that enables production planners optimally to introduce a new product into a suitable production line. The fit of the new product with the existing mix is considered and the dynamic nature of the product mix is also considered. DFGMA can also be used as a tool for performing sensitivity analysis for various costs, productivity levels, product configuration, mix assumptions at each facility, or analysis of parameters of interest to design, marketing and manufacturing. The mathematical model was formulated as a mixed-integer linear program (MILP) where the objective function specifies the minimization of all costs associated with the design, manufacture, inventory, transportation, logistics, set-up, tooling and capital procurement, to support the introduction of a new product. Six different types of constraints were included in the model. The LINDO software package was used to solve the model. Further work can be done in evaluating the use of the DFGMA model for concurrent sourcing decisions of multiple new products to sites characterized by various existing mixes. Reallocation of some existing capacity to different existing plants, or the addition of new plants may prove especially interesting. In addition DFGMA should be tested in situations with more explicit model market timing issues. Another area of research interest is the applicability and evaluation in a real system.

Tu (1997) presents the basic concepts and methods, a reference control structure, and a reference company architecture to cope with the particular problems for production planning and control (PPC) in a virtual OKP (One-of-a-Kind Production) company. Today, the manufacturing industry, particularly the 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 area, have become virtual companies. The particular problems discussed in this paper include: (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) adaptive production scheduling structure and algorithms to cope with the uncertainties of a production state in virtual OKP; (5) modelling of production states and control system in a virtual OKP; and (6) the reference architecture for a virtual OKP company.

Sarmiento and Nagi (1999) reviewed recent work in the area of integrated analysis on systems that explicitly consider logistics (transportation systems) integrated into other functions in production, and also they identified areas where further research is needed. In addition, the authors were interested in identifying work done at the strategic or tactical level. They classified the papers about production, distribution and inventory planning based on the type of decisions to be taken in the model and on the number of locations per echelon in the model. They also differentiate the work for which an expedited transportation mode is included. The inventory/routing was also analysed. Among the conclusions, the authors state that the integration of the logistics function into the analysis of previously isolated production functions has the potential of providing significant benefits to companies, in the form of cost savings and efficiency improvement.

One problem encountered in forming a virtual corporation is to assign tasks to each partner and to schedule the production based on the capabilities of each one of them; from table 10 we can see that two papers were centred in this problem. One was concentrated in setting up the basics for a virtual OKP company and the other reviewed work on integrated systems. None of the papers analysed developed software prototypes or reported quantitative benefits. Only two out of the four developed a mathematical formulation, and a solution methodology. One used the authors own modified heuristic and the other LINDO software. Don-Taylor (1997) also reported the inclusion of sensitivity analysis while solving the model. To compete in the present market environment, Sarmiento and Nagi (1999) remark that it is important to have an integrated production planning, scheduling and control system.

Author	Objective (purpose)	Approach	Limited to
He and Kusiak (1996)	Develop models for allocation of workload among partners and determination of production schedule for given product structures in a virtual company.	It considers that any virtual corporation is formed by manufacturing centres (MC) and assembly centres (AC). First solved the product allocation problem for the AC adapting the rotation cycle schedule (RCS). Then solved the scheduling for the MC.	Virtual corporations.
Don-Taylor (1997)	Develop a mathematical tool that enables introduction of a new product into a suitable production line in a multi-facility, global environment. Introduce Design for Global Manufacturing and Assembly (DFGMA).	A general mathematical formulation is presented and tested under realistic conditions. This model explicitly considers product mix, process configuration, and capital procurement strategies, as well as tooling, design, and set-up costs associated with manufacture and assembly.	Multi-facility in global environments.
Tu (1997)	To set-up the basic concepts and methods, a reference control structure, and a reference company architecture to cope with the particular problems for production planning and control.	A dynamic hierarchy control structure under the virtual production control concept was proposed to cope with frequent changes. An adaptive production scheduling system structure and the algorithms were proposed to cope with uncertainties. And a network state variable and network state space were proposed for modelling production states and control system.	Virtual one-of-a kind production (OKP) company.
Sarmiento and Nagi (1999)	Review recent work on integrated analysis of systems that explicitly consider logistics integrated to other functions in production. Areas of further research were identified.	Development of a classification of the inventory/distribution and production/distribution problems based on the type of decisions to be taken in the model and on the number of locations for echelon in the model. The inventory/routing problem was also analysed.	Models of production-distribution systems with transportation included.

Table 10. Production planning, scheduling and control. Comparison of papers.

3.4. *Facilities design and location*

The problem of facility layout and location for agile manufacturing environments has been studied in the literature. This category has been divided in two sections. The first is about facilities design and the second is about facilities location (see table 1).

3.4.1. *Facilities design*

In this section, we will report several papers. We found three different approaches. Table 11 shows three different types of layouts that researchers have explored. They are holographic, fractal and virtual. Venkatadri *et al.* (1997) and Montreuil *et al* (1999) propose a methodology for designing jobs shops under the fractal layout organization that has been introduced as an alternative to the more traditional function and product organizations. Fractal layout with a nearly square arrangement of machines is the safest choice for agile manufacturing according to the authors. They first begin with an illustration of how a fractal job shop is constituted from individual fractal cells. Then they consider joint assignment of products and their processing requirements to fractal cells, the layout of workstation replicates in a fractal cell and the layout of cells with respect to each other. The main challenge in assigning flow to workstation replicates is that flow assignment is, in itself, a layout dependent decision problem. They confront this dilemma by proposing an iterative algorithm that updates layouts depending on flow assignments, and flow assignments based on the layout. The proposed heuristic is computationally feasible; the authors experiment with test problems taken from the literature. They conclude by showing how the methodologies developed in the paper have helped to evaluate fractal job shop designs through specification of fractal cells, assignment of processing requirements of workstation replicates, and development of processor level layouts. This step has had the far-reaching consequence of demonstrating the viability and the validity of the fractal layout organization. One disadvantage is that

Author	Layout type	Approach
Venkatadri *et al.* (1997) and Montreuil *et al.* (1999)	Fractal	A decomposition was used to perform assignment and layout of tasks. The process is initiated by capacity analysis and workstation allocation (fractal cell creation), and after performing these tasks, an iterative algorithm that updates layouts depending on flow assignments, and flow assignments based on layout was employed.
Montreuil *et al.* (1991)	Holographic	Decomposes the layout design in two phases. The first phase finds mini-max positions for each workstation, and in the second an assignation of workstations to available locations is made.
Irani *et al.* (1993)	Virtual cells	Combination of graph theoretic and mathematical programming concepts applied to GT cell layout design. The layout design problem was split in two parts. The first part generates a maximal spanning arborescence and the second part reorders the branches of this arborescence finding the optimal orientation that minimizes travel distances and machine duplication.
Venkatadri *et al.* (1996)	Comparison	Evaluation of fractal and holographic layouts, and comparisons with functional and pure groups layouts.

Table 11. Facilities design. Comparison of papers.

each layout encapsulates multi-process functionality, thus making it more diverse and thereby more difficult to manage.

Montreuil *et al.* (1991) introduce the concept of 'holographic layout' as a robust alternative to process layout in such job-shop-type manufacturing systems operating in highly volatile environments. The basic idea is not to create any cell, but rather to spread the workstations of each type throughout the manufacturing facility. This aims at ensuring the proximity of a workstation of any type from each workstation of any other type so that precise routings that are flow efficient can be created in real-time by a computer integrated manufacturing planning and control system. The objective is to ensure robustness of the layout in terms of flow travel by optimizing the dispersion of the workstations of each type. The strategy is to use a minimax design objective. This means to minimize for every workstation of every type, the maximum distance between the workstation and the nearest workstation of each other type, weighted by the expected number of trips to and from the workstation. They decompose the layout design task in two phases. For each workstation type, the first phase of the proposed heuristic finds minimax positions for each workstation given the number of such workstations. This is achievable optimally in polynomial time when the distances are rectilinear, and heuristically when distances are computed using a more complex metric. The second phase then proceeds to assign the complete set of workstations to the discrete set of available locations. The linear assignment model is used to efficiently assign workstations to grid locations so as to minimize the sum, over all workstations, of the weighted distance between the location where the workstation is laid out and its minimax location as computed in phase one. Comparing the expected distance travelled by a lot every time it moves from a workstation to its next required workstation, the holographic layout had a significant 35% improvement with respect to the process layout in the numerical study. The authors provide an explanation about why 'holographic' was chosen to name this type of layout. This study does not include in its analysis input and output stations. They took seven cases from literature to evaluate their proposal. They found for these seven cases that function layout and holographic layout used the least number of workstations, and the fractal layout performed in five out of seven cases very well with respect to flow distance. The methodology proposed for holographic layout does not specify clearly, the rules that must be followed for cell creation (see table 12).

Irani *et al.* (1993) develop a flow-based approach for the formation of virtual manufacturing cells. This method generates machine groups, identifies a flow-line layout for each group and indicates which flow-lines must be placed adjacent to each other to minimize intercell flow distances. The concepts of a hybrid cellular layout and virtual manufacturing cells are related. It is shown that a combination of overlapping GT cells, functional layout and handling reduces the need for machine duplication among cells. This approach questions the traditional emphasis on machine duplication to create independent cells that is suggested by the standard machine–part matrix clustering methods. The steps in the method are demonstrated by using two illustrative examples obtained from the literature.

Venkatadri *et al.* (1996) experimented to find out whether the fractal layout provides flow efficiencies similar to the group layout and capacity requirements equivalent to the function layout. Seven cases were analysed by the following four basic job shop designs: function layout, pure group layout, holographic layout and fractal layout. Since different number of workstations were involved in the different

Authors	Mathematical formulation	Heuristic used	Variables analysed	Development of software
Venkatadri *et al.* (1997) and Montreuil (1999)	Multi-commodity network flow linear programming for flow assignment	Modified Ford–Fulkerson technique	Flow distance score and capacity requirements	Yes, in C. Also used CPLEX v3.0 on a SUN 4c platform running Sun OS 5.3
Montreuil *et al.* (1991)	Linear assignment model for phase 2	Hungarian algorithm	Expected distance travelled	None
Irani *et al.* (1993)	Linear programming for phase 1 and integer programming for phase 2	LINDO	Intercell flow distance	None
Venkatadri *et al.* (1996)	None	None	None	None

Table 12. Facilities design. Comparison of papers.

designs, they assumed that the shop was constrained to a rectangular grid with similar aspect ratios. All workstations were assumed to be unit squares within this grid. Flow distance and number of machines in the design were the criteria of comparison between different designs. Rectilinear distance was used as a measurement of flow distance. Some of the results of this paper were as follows. In all cases, the function and holographic layouts use the least number of workstations, in other words they perform best with respect to capacity requirements. The function layout is the one that has worst flow performance in all cases. The group layout performs the best in flow distance in two out of seven cases. In terms of capacity, it is the most expensive in all cases. Fractal layout is a flexible hybrid layout that combines good features of both function and group layouts. For the authors, it seems that the results have sufficient indication that the fractal layout will avoid the pitfalls of excessive workstation duplication and yet not compromise on flow distance. They also stated that holographic layout is a serious competitor to the fractal layout since its performance is quite comparable despite the obvious disadvantage that it is not the recommended design for shops with known product routings. We can see in this report that the comparisons were made between layout designs created for traditional environments and layout designs created for dynamic environments. As the authors of this paper express, measures of flexibility and robustness under variations in design parameters must be incorporated to the research. In addition, time response to changes in product routings variations, as well as work-in-process and lead times, are measures that this study does not consider.

3.4.2. *Facilities location*

In this subsection are included articles that are not specifically focused on agile manufacturing environments. They analyse the facility location problem for international or global environments. However, facility location problems considering global environments is an important part of agile manufacturing systems. Syam (1997) proposes a model and efficient heuristic solution methodology for an extended facility location problem involving not only a restriction on the total number of open facilities, but also (i) limits on the total number of open facilities, (ii) limits on the number of open facilities in particular regions of the world, and (iii) the availability of a number of capacity options at each location. A highly efficient heuristic solution methodology based on Lagrangian relaxation is provided, and problems involving up to 400 locations/destinations are solved. In addition, the paper investigates various logistical issues that are of relevance to managers in the current era of globally dispersed facility locations. One limitation of this work is the assumption that every region must have the same number of open facilities; this is not true in the real-world.

Canel and Khumawala (1997) survey the available literature on international facility location. They formulate the uncapacitated multi-period international facilities location problem using a mixed-integer programming, and provide an efficient branch-and-bound procedure for solving. This branch-and-bound procedure is applied to a case study and tested for its efficiency. The solutions and computation times are compared with those obtained using LINDO. This extensive computational analysis has been extremely promising.

Haug (1992) studies the global location decisions of high technology multinational companies and the cost dynamics experienced in manufacturing a single product over time. A set of assumptions and variable cost functions are developed to model a high technology firm's locational choices and transfer of production from domestic to foreign manufacturing sites. A methodology that converts the multiple period problem into a network design is presented. This solution algorithm enumerates all possible combinations of plant and country locations to produce the optimal sequence of production locations that minimizes the total cost of manufacturing a single product over a specific time horizon. An application of the mathematical model to a multinational enterprise scenario was illustrated.

In summary, a new generation of layouts was deemed necessary for new and dynamic manufacturing environments that need to adapt to changing products and technologies, pressures to reduce lead times and inventories, compulsions to customize products, through quicker product changeovers, and just-in-time deliveries. As part of this new generation, fractal, holographic, and virtual layouts were analysed. In addition, global facilities locations approaches were presented.

3.5. *Material handling and storage systems*

A material handling system can be simply defined as an integrated system involving activities such as handling, storing, and controlling of materials. The primary objective of using a material handling system is to ensure that the material in the right amount is safely delivered to the desired destination at the right rime and at minimum cost. Agile manufacturing systems require an efficient system for their storage and retrieval together with a material transportation system because of its characteristics of frequent and quick changes. Meller and Mungwattana (1997) illustrate how multi-shuttle systems may be used to meet the requirements of agile manufacturing and electronic data interchange (EDI)-based distribution. They note that automatic storage/retrieval systems (AS/RS) must increase their throughput and responsiveness. The authors develop analytical models for various multi-shuttle AS/RS command cycles under heuristic operating policies and illustrate the accuracy of their models by comparing their results with Monte Carlo simulation results. The paper shows that a twin- or triple-shuttle system operating under quadruple command or sextuple command policies, respectively, has a higher throughput capacity than a single shuttle system operating under dual-command. Furthermore, the performance of the twin- and triple-shuttle systems can be significantly enhanced by using an improved strategy of storing and retrieving at the same location when possible. The authors call them modified quadruple-command (MQC) and modified sextuple-command (MSC). Instead of using modified command cycles with first come, first served (FCFS) retrieval within a cycle, they propose implementing operating policies called nearest neighbour (NN) and reverse nearest neighbour (RNN). With such policies, the travel time is reduced by reducing the travel time between storage and retrieval locations. The NN and RNN policies exhibit good performance and are also practical to implement. Automated systems offer many advantages over conventional storage systems. Meller and Mungwattana's research is focused on these systems, but hardly any other work was found in this category.

3.6. *Information systems*

Frequent and dynamic interactions among partners in agile manufacturing entails the crucial role of a flexible dynamic and integrated mechanism to manage partner information flow. Traditional information systems do not accommodate reconfigurability and composability, since they are monolithic with no consideration to change. A new approach is necessary. This section will show the efforts that researchers have made to provide a new breed of information systems for agile manufacturing enterprises. Given the number of papers found, a sub-classification is presented in table 1, and is developed in the following.

3.6.1. *Integrated information systems*

The characteristics of an agile manufacturing enterprise require an integrated information system between collaborators. Mills (1995) describes the basis for the Systems Integration Architecture (SIA) project of Aerospace Agile Manufacturing Research Center (AAMRC) from the viewpoint of the services it provides. These services provide the infrastructure for an agile information system. SIA provides a framework for the 'integration' of FTAs (Functional Transformation Agent) and allows their composition into process by a variety of methods. Methods included are a prescriptive, predefined work-flow management approach, random selection of FTAs with automatic checking for the existence of an aspect with the correct modality, hierarchical organization, intelligent or responsible agents, and automated process creation and execution using automated planning systems. To facilitate the integration of the FTAs, an infrastructure provided by three modules: the executive, the librarian, and the communication kernel was developed. SIA provides at least an initial attempt at integrating the relationships among all the data sets. The concept of the Librarian provides for their management, at least in theory.

Song and Nagi (1996, 1997) propose an information framework for virtual enterprises, such that distributed information can be shared by partners at various collaborative levels while inter-database dependencies are maintained dynamically, and the information flowing in/out of a partner is controlled by the management policy of the partner. An individual partner, with its information system, can plug in (out) of the virtual enterprise supported by a communication network such as the 'Factory America Network'. It is through the integration of these partner information systems that information management is possible in collaborative activities. The main contributions of these papers include the following: (1) Development of an agile manufacturing information system (AMIS) framework, which provides interoperability between partners databases and assures data consistency among partner databases. (2) Design of the AMIS model, which includes information hierarchy, the transaction hierarchy and the knowledge base: (i) the information hierarchy represents virtual enterprise information using object-oriented methodology (OOM); (ii) the transaction hierarchy uses a partner query language to compile queries and a partner work-flow language to specify partner work-flows; (iii) the knowledge base system (KBS) is built based on the partner policies and protocols. The modelling and validation of transaction procedure knowledge is accomplished using Petri nets. (3) Implementation of the prototype system, which integrates the distributed partner information using a client/server architecture. Through the process of framework development and prototype system implementation, the authors come up with a thorough approach for building partner self-supporting information systems, to plug into the agile manufacturing network and form virtual enterprises.

Strader *et al.* (1998) propose an information infrastructure framework for supporting management of electronic virtual organizations. They identify the life cycle phases and their associated decision processes. The organization's life cycle is made up of the identification, formation, operation and termination phases. Each of the phases is made up of two or more major decision processes. They describe the requirements for an information infrastructure to support the management of virtual organizations throughout their life cycle, and discuss how inter/intranet technologies provide the mechanisms required for virtual organization management. The importance of information infrastructure to virtual organization management is illustrated through a set of simulations that compare performance of traditional static (stable partnership) supply chains and dynamic (virtual) supply chains utilizing a dynamic material allocation (DMA) strategy to respond to environmental change. The overall conclusion of this paper is that an information infrastructure, utilizing internet and intranet technology, can support the communication required for effective virtual organization management throughout its life cycle.

3.6.2. *Information systems designed for supporting specific areas*

Ten articles were reviewed for this subsection. These articles designed information systems for supporting specific areas. The areas are production planning, product design, computer integrated manufacturing and ordering systems (see table 13). Zhou *et al.* (1998) and Zhou and Besant (1999) present a distributed information management architecture for production planning and control in semiconductor manufacturing virtual enterprises (SMVE). The architecture and its detailed design have partially been implemented and tested in the X-CITTIC project. Object-

Author	Area supported
Zhou *et al.* (1998)	Production planning
Zhou and Besant (1999)	Production lanning
Govindaraj (1997)	Design process
Wiebe (1997)	Design process
Jain (1995)	Design process
Wang *et al.* (1996)	CIM
Aoyama (1998)	Development of software
Pradhan and Huang (1998)	Ordering system
Wong *et al.* (1996)	Ordering system
Veeramani and Joshi (1997)	Ordering system

Table 13. Information systems designed for supporting specific area. Comparison.

oriented technologies are widely used in its design and implementation. A concept for an information management component is proposed in these papers to manage the information within a SMVE. The component can be attached to each virtual enterprise unit to integrate local information, and provide it to local and remote applications. A detailed structure of the components in the architecture, called information managers, is also suggested and introduced. Each information manager has three elements: a data object server, a database and a group of meta-objects. It can provide not only basic services (e.g. read and write) but also advanced services (e.g. notification, security control, subscription and data sending, data conversion, etc). To capture all of its important aspects, three kinds of models—object, dynamic and functional—are presented to describe it from different viewpoints.

Govindaraj (1997) describes the outline for an information system that assists designers. It is being developed and implemented in parallel with detailed empirical studies of actual designers. The system architecture incorporates software agents in a distributed client/server environment. The computational architecture for design support is characterized by a two-step process, one 'bottom-up' and the other 'top-down'. Identification and adaptation of the computational tools relevant for the functions and processes found in the current design practice constitute the bottom-up component. The top-down component comprises analytical and formal 'engineering' approaches to design, derived from the disciplinary contexts, laws of nature, corporate policies and 'styles', and societal and other constraints. Design practices in a corporate usability laboratory of a transnational company were studied. The company designs and manufactures electro-mechanical components and environmental control systems used and serviced by people with a variety of backgrounds. While the staff of the usability laboratory are not typical engineering designers, since their primary design responsibilities concern user interfaces, they play a significant supporting role to engineering designers in the company. Recommendations and suggestions are provided for implementing an information system for the usability laboratory. After implementing and evaluating the system in actual design environments, the author plans to evolve the system into a collaboration pool, and later, into an active assistant or associate that performs some of the design tasks.

Wiebe (1997) examines the fact that agile manufacturing goals demands technologies that support group activities in the design stage. This work proposes a theoretical structure by which the impact of CAD/PDM (Computer Aided Design/Product Data Management) tools in an organization can be evaluated. Product Data Management systems allow for the linkage of groups that are both dispersing and accessing information. CAD combined with PDM (Product Data Management), can enhance a creative and innovative design process and improve quality and time to market through more meaningful information exchange.

Wang *et al.* (1996) present a network CIM (Computer Integrated Manufacturing) or an internet assisted manufacturing system for agile manufacturing. This system can be applied to advanced FMS (Flexible Manufacturing Systems) units or smart machine cells as well as common CNC (Computer Numerically Controlled) machines, with an intent of shortening the manufacturing cycle and improving the agility of the manufacturers. This system consists of a CAD/CAPP/CAM/CAA (Computer Aided Design/Computer Aided Process Planning/Computer Aided Manufacturing/Computer Aided Assembly) integrated Central Network Server (CNS), which links to local FMS, or CNC machines by means of cable connections. After a local user inputs the product information, the CNS can generate complete CAD/CAPP/CAM/CAA files and control the remote FMS or CNC machine to accomplish the whole production process. This system uses the internet as an interface between a user and the CNS and allows a local user to operate remote machines connected to the internet. This paper also proposes to build a network of manufacturing databases and a research database to improve the manufacturing agility.

Jain (1995) describes the role of modelling and analysis during the manufacturing system development cycle and proposes a Virtual Factory Framework (ViFF) for their systematic and efficient use. The use of ViFF would minimize the need for debugging new or modified manufacturing systems. This paper defines ViFF as a computer-based system that will provide a common operating environment and integration mechanism for modelling and analysis tools used in the manufacturing system development process. In this ViFF the users are connected via a common communications and control framework to the tools and services needed in the manufacturing system development process. An information management system and a virtual factory test bed are included as part of the virtual factory framework structure. Ease in accommodation of framework elements in a plug and play context is central. Potential ViFF users include managers, plant designers, planners, manufacturing engineers, test personnel, plant integrators, and industrial engineers among others. The baseline for the modelling and analysis is the 'Manufacturing cube model'. This model consist of stages, functions, and levels, each one described in this paper. The development of this ViFF is still in progress and several goals were defined for the project.

Aoyama (1998) describes the Agile Software Process (ASP), a new process model that tackles the accelerated pace of software development and the geographically distributed nature of many development teams. Two methods play a central role in managing ASP: the time-based process enaction model and just-in-time process management. These methods are embedded into a process-centred software engineering environment called Prime. The Agile Software Engineering Environment design is based on the following concepts: support for just-in time management of both process and product, a network-centric architecture and support for the individual developer.

Pradhan and Huang (1998) deal with the implementation of a three-tier database system, using Java (the programming language from Sun Microsystems) and JDBC (Java Database Connectivity) , and creation of an innovative, intelligent 'interactive ordering system' on the internet. It goes a step further to prove the flexibility of the system, by using different database engines at different nodes.

Wong *et al*. (1996) describe the framework for a computer-integrated system, QUESTER, that provides customers with the ability to customize electronically the product of their choice through the internet and receive a real-time response regarding the price and delivery date for the desired product along with the image of the CAD model of the customized product. If these terms are acceptable, the customer can place an order for the customized product and enter it into the company's manufacturing schedule. Thus, by combining several technologies, including solid modelling, the world wide web (www), manufacturability assessment, rapid cost estimation, and dynamic planning and scheduling, QUESTER presents a novel approach for significantly enhancing a company's responsiveness to a customer.

Veeramani and Joshi (1997) present a new paradigm for processing RFQs (request for quotations) and describe methodologies for rapid and accurate estimation of manufacturing cost for modified standard products and custom-made products. Insights gained through industry collaboration on the development of rapid cost estimation systems are also discussed. They focus on single-tier interaction between only two parties (namely a customer and a vendor). Two different approaches are used depending of the product. A product-similarity approach for cost estimation of modified standard products, and a routing-similarity based (or variant-generative based) approach for cost estimation of custom-made products.

3.6.3. *Architectures: requirements and implications*

Jung *et al*. (1996) provide a primary sketch of architectural requirements for rapid development of agile manufacturing systems. They identify all the architectures necessary to develop the automated CIM system and propose a reference architecture for each identified architecture. The necessary architectures are control architecture, function architecture, process architecture, information architecture, communication architecture, distribution architecture, and implementation architecture. The reference architecture is expected to provide a transparent way to the users when they establish the automated CIM systems.

Johnson and Reid (1997) discuss the development of the design requirements for a strategic information system by the Agile Aerospace Manufacturing Research Center (AAMRC). The system design requirements were developed using IDEF0 and Quality Function Deployment for the enterprise activity and the user view, respectively. The IDEF0 model of the strategic management processes was developed through the structured analysis and design technique, and includes the use of the author/reader review cycle to develop consensus. Quality Function Deployment was used to collect user requirements not easily uncovered and recorded during the creation of the IDEF0 model. These requirements were compared with the enterprise information strategy to develop other requirements. These requirements led to a phased implementation approach of the strategic information system.

Weston (1998) describes the important role that software-based integration infrastructures and integration structures can play respectively in supporting and organizing system behaviour in a way that facilitates system extension and change. Weston (1998) also describes different types of reusable software component and their infrastructural needs. These components are likely to become common building blocks of next-generation agile manufacturing systems. The paper illustrates the concepts described by reporting on research in the Manufacturing Systems Integration (MSI) Research Institute, which is producing proof-of-concept agile manufacturing systems in collaboration with UK end-users and vendor companies.

Smith and Wolfe (1995) describe how Client/Server systems have emerged as a pragmatic form of distributed systems. They represent a pro-active market driven migration path for companies that are being driven to the new Virtual Corporation organization paradigm. They analyse current architectures of client/server systems and their features. The client/server systems discussed in this paper are: (1) relational/fourth generation language (4GL)/graphical user interface (GUI)/structured query language (SQL); (2) groupware/multimedia/document management; and (3) object oriented/GUI/class libraries.

3.6.4. *Information exchange*

Recent advances in communications technology make it possible for manufacturers to transmit data to each other in fractions of a second. However, if these corporations do not use the same software tools, understanding of the data can be delayed for weeks or months while employees purchase and learn to use new tools. This subsection describes research that seeks to use standards to reduce the problems that occur when manufacturers want to use different tools to process each other's data. Hardwick *et al.* (1996) describe a prototype information infrastructure for virtual manufacturing enterprises. This infrastructure combines the internet with the standard for transfer and exchange of product model data (STEP) and the common object request broker architecture (CORBA) standard for interoperation of application systems. The prototype shows how applications described by CORBA can be applied to data defined by STEP on the internet. The combination allows manufacturers to share information about products over the internet while using their favourite tools to process the information. To create the infrastructure, the data definition language of CORBA, IDL (interface definition language) is combined with the data definition language of STEP, EXPRESS. These two languages have different purposes: IDL describes interfaces to applications; EXPRESS describes normalized data models. Both can be used to describe objects for manufacturing applications.

Koonce *et al.* (1997) present an integrated database model that serves as the basis for manufacturing information exchange. Termed the Unified Data Meta Model (UDMM), this structure is based on common relational data modelling methods and was developed to support the integration of computer aided design (CAD), computer aided process planning (CAPP), numerical control (NC) tool path verification and material requirements planning (MRP). From this structure, application interfaces can identify overlapping data and agree on the format of exchanged information. The specification of the UDMM, and the nature of the integration architecture in which it exists, allows for extension of both attributes in the model and new entities as new domains are added.

3.6.5. *Evaluation of information models*

Pant *et al.* (1994) present a reference model that is based on, and also extends, previous results. It is used to evaluate an existing computer integrated manufacturing (CIM) information model that was developed based on status-quo systems and revises it with more ability to the support concurrent process for agility. The main contributions are the reference model and a case study. The reference model employs the paradigm of parallel formulation. The case study of the model was conducted on the existing CIM model at Rensselaer Institute and is described to evaluate and reformulate the previous processes. The results show a better design featuring concurrent execution of functions, which in turn support agility and adaptiveness. It was demonstrated that by analysing functions, sub-processes comprising the shop floor control system can be broken down to elemental task and data requirements; and that analysing the knowledge inherent in their interactions, these tasks can be regrouped into parallel processes to share larger decision spaces.

In summary, this section devoted to information systems, has reviewed papers focused on this important aspect, which every agile manufacturing enterprises must consider. Table 1 shows the classification of the papers compiled for this topic. Five different subtopics were presented where 'Information systems designed for supporting specific areas' was the subtopic with the most number of papers reviewed (10 out of 21).

3.7. *Supply chain*

Supply chain management is the competitive arena of this era. While management of the supply chain is not new, more firms are beginning to give it the importance it deserves. For this topic we found articles that were classified into two areas: strategies, and partner selection. Both subtopics will be developed in the following.

3.7.1. *Strategies*

This section presents strategies proposed by different authors. Naylor *et al.* (1999) propose that the lean and agile paradigms, although distinctly different, can be and have been combined successfully within total supply chains. The authors show how the need for agility and leanness depends upon the total supply chain strategy, particularly by considering market knowledge and positioning of the decoupling point. The decoupling point separates the part of the organization (supply chain) oriented towards customer orders from the part of the organization (supply chain) based on planning. The decoupling point can also be defined as the point at which strategic stock is often held as a buffer between fluctuating customer orders and/or product variety and smooth production output. Location of this decoupling point is critical when considering to adopt agile or lean manufacturing techniques. The authors of this paper affirm that the position of the decoupling point depends upon the longest lead time an end-user is prepared to tolerate and the point at which variability in product demand dominates. Downstream from the decoupling point all products are pulled by the end-user, that is, they are market driven. Upstream from the decoupling point the supply chain is initially forecast driven. Depending of the position of the decoupling point the authors distinguish five classes of supply chains. Buy-to-order, make-to-order, assemble-to-order, make-to-stock and ship-to-stock. On the downstream side of the decoupling point is a highly variable demand with a large variety of products and, upstream from the decoupling, the demand is smoothed with the variety reduced. This indicates that the point of product differentiation is at, or downstream from, the decoupling point and the stock held at the decoupling point acting as a buffer between variable demand and a level production schedule. The authors coin the term 'leagility' for their strategy because it involves the use of both paradigms. The lean paradigm can be applied to the supply chain upstream of the decoupling point as the demand is smooth and standard products flow through a number of value streams. Downstream from the decoupling point a number of products flow through one value stream. The agile paradigm must be applied downstream from the decoupling point as demand is variable and the product variety per value stream has increased.

Mason-Jones and Towill (1999) demonstrate in this paper the power of the Total Cycle Time (TCT) compression paradigm applied to complete chains. To calculate TCT it is necessary to sum the material flow delay and the information flow delay. They remark that slashing of process lead times throughout the chain is not enough to enable agility. In addition, a reduction in information lead times 'information enrichment' must be done. Thus, in order to establish an agile framework, both the material and information flows require analysis to establish the influence each has on the improved performance. A simulation at the retailer stock level was carried out in order to appreciate the effect of both reductions. The authors benchmark the improvements against a traditional supply chain, and provide several existing barriers to implementation of 'information enrichment'. In addition, they provide a recommended route map, which is very general and does not offer new methods for implementation. Using their simulations, the authors could extend their results and offer to supply chain members more detailed steps in the implementation of TCT.

Weng (1999) develops a model for a two-echelon distribution system with n retailers, each of which supplies normally distributed demand of m products having modular product design. This paper proposes to employ the joint buffer stock as a solution of out of stock products sharing modularity. The author investigates the value of the retailer joint buffer stock, and develops managerial insights into the impact of employing joint buffer stock at a retailer level. In other words, this paper studies the effect of risk-pooling over demand uncertainty of multiple products sharing product modularity. The analytical results indicate that significant savings due to employing joint buffer stock at each retailer reach a maximum when the variance of end-of-period net inventory is identical for all retailers and all products. Additional results show that the higher service level desired, the more effective is employing joint buffer stock; it will lead to a lower minimum expected system cost, even when the unit purchasing price of joint buffer stock is relatively more expensive than the substituted products. Further work is possible considering that the expected inventory at the end-of-period does not follow a normal distribution.

Hoyt (1995) addresses supply chain alliance research for agile organizations that draws on theories from transaction cost analysis, resource-based analysis, strategy-structure and human resources. This paper has five objectives: (1) to provide an overall discussion of the factors that contribute to the success or failure of customer-supplier alliances; (2) to investigate the current status of research on customer supplier alliances with respect to transaction cost theory, resource-based theory, strategy-structure theory, and human resource theory; (3) to review the current empirical research that has been published to evaluate models and operationalization of relevant constructs; (4) to compare US alliances with the Japanese alliances; (5) to develop two additional proposals that extend the current theories of Customer Supplier Alliances.

The company that masters the ability to reconstitute its supply chain will have the means to act when the opportunity presents itself as well as when innovation promises an advantage. But the situation is that these new supply chain strategies are ephemeral like any other business strategy. For those who master them early, they can use that mastery to advantage while others lack it. If, in fact, these strategies are good operating modes every company will try to master them. The advantage will then go away and the mode will not be useful in competitive leadership. Hence new strategies will have to be proposed.

3.7.2. *Partner selection*

'One of the things that distinguish agile manufacturing from lean production, is that you can be lean by yourself, but you can not be agile by yourself. In fact doing business with companies that are not agile can impede your own agility' (Sheridan, 1993). In this changing market, management must be prepared to approach outside organizations, present their single view of the future and build relationships/partnerships that recognize value in a standardized interaction. As a consequence, it is necessary to develop methodologies for the evaluation and selection of partners.

Papers about partner selection and evaluation were reviewed in this subsection. Sarmiento and Nagi (1998) and Sarmiento (2000) formulated the problem faced by the coordinator of the organizational web in an agile manufacturing environment. The problem can be stated as selecting an optimal set of partners for the creation of a virtual enterprise capable of responding to a given market opportunity. A mixed integer linear program (MILP) was formulated, taking into account production, inventory holding, production set-up, backlogging, transportation, and fixed costs incurred when partnership between two companies is established. A heuristic solution approach has been presented, which represents the problem as a network and is based on the utilization of a k-shortest paths algorithm. The results observed from the numerical study indicate that the heuristic performs well compared with the solutions obtained from the MILP solver. However, as the dimension of the problem grows with the number of nodes and time periods considered, the use of a commercial MILP solver such as CPLEX to obtain an optimal solution to the problem is no longer feasible. Sarmiento (2000) found that the limit will be for networks with about 50 nodes and 10 time periods. In order to solve larger networks or cases with a higher number of time periods, a decomposition approach based on a column generation scheme was proposed.

Talluri *et al.* (1999) propose a two-phase quantitative framework to aid the decision making process in effectively selecting an efficient and compatible set of partners. In this paper they incorporate into one decision model both the internal decision variables for analysis of candidates of a given process type, and the external (compatibility) analysis of candidates for different process types. Phase 1 is a filtering technique based on the external relationship decision variables of the candidates. This technique identifies 'efficient' candidates for each type of business process. The input/output measures for each business process type are also identified within this stage. This filtration results in a reduced set of possible combinations that are considered in Phase 2 of the analysis. A specific data envelopment analysis (DEA) model referred to as the CCR (Charnes, Cooper and Rhodes) model is applied in Phase 1. The CCR model is a fractional programming technique that identifies efficient candidates by incorporating a range of internal activity and performance measures into the model. Phase 2 utilizes an integer goal programming model, which is based on external decision variables (compatibility criteria), for selecting an effective combination of candidates to participate in the formation of a value chain network (VCN). An illustrative example is given using hypothetical data. There are two concerns about this work. One is the filtration of initial data at the beginning of the optimization procedure, which can provide a sub-optimal solution. And other is the determination of the input and output factors that should be considered for the analysis. Further extension of this work can be how to restrict weights in the initial filtering process for a very effective differentiation between performers. In other words, a more robust initial filtering process will be expected. This study is performed from the standpoint of brokers, but can also be performed from the standpoint of a lead business. Additional considerations are how VCN workers will divide their loyalty between their original corporation and the new venture.

Gupta and Nagi (1995) develop a flexible and interactive decision support system to aid in optimal selection of manufacturing partners for a business initiative in an agile manufacturing environment. This decision support system formally combines concrete quantitative information as well as user's fuzzy qualitative information, providing quick and near optimal selection of partners. The approach starts with the construction of an AHP comparison matrix with default pairwise evaluation of attributes using fuzzy functions, at the same time, the user provides priorities for each attribute, then both pieces of information are combined and synthesized by Fuzzy-AHP to give relative priorities. A genetic algorithm is the next step in this approach that provides near optimal groups of manufacturing partners that best satisfy the requirements of the new enterprise.

Gupta and Nagi (1996) develop a variant to the interactive decision support system proposed by Gupta and Nagi (1996), the new system is based on an entirely linguistic selection methodology. The decision making process consists of the following steps: (1) selection of attributes and levels of importance in a fuzzy linguistic form; (2) generation of all feasible alternatives using a depth-first explicit enumeration technique; (3) evaluation of every feasible alternative and selection of non-dominated alternatives; this iterative segregated step uses the fuzzy evaluation technique suggested by Liu *et al*. (1994); (4) Selection of the best non-dominating alternative using the 'linguistic decision making technique'. Given that the approach used explicit enumeration of all possible alternatives, this methodology may not be suitable for problems involving a large number of processes and partners.

Herrmann *et al*. (1995) identify three stages in the selection of partners: 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. This paper presents a new information model that describes the systems, process capabilities, and performance of a manufacturing firm. They implemented the model and used it as part of a decision support system for design evaluation and partner selection in agile manufacturing.

Candadai *et al* (1995) and Herrmann and Minis (1996) describe a variant approach to evaluate, early in the product life cycle, a proposed design with respect to the capabilities of the potential partners. The result of this work is an integrated system for design evaluation and partner selection for flat electro-mechanical products. Using this system, a designer can define a feature-based product model, generate concise product descriptors, search for and sort similar products, generate alternative plant-specific process plans, evaluate those plans, and compare them to find the most suitable combination of processes and manufacturing partners. The main strength of this variant approach is the integration of the following issues related to variant design critiquing: hybrid feature-based product modelling, automated generation of Group Technology codes, concise but detailed product description, and the accurate and rapid retrieval of designs and process plans of similar products. Additional research is needed for non-flat parts and non-mechanical parts.

Minis *et al*. (1999) describe a generative approach for concurrent manufacturability evaluation and partner selection. The approach evaluates the manufacturability of a proposed design with respect to the capabilities of candidate partners and allows the product development team to select a partner based on its ability to manufacture quickly and inexpensively. The generative approach developed consists of three procedures: feasibility assessment, manufacturability assessment, and plan synthesis. Feasibility assessment generates feasible process and partner combinations. Manufacturability assessment evaluates these combinations. Plan synthesis combines this information and presents alternatives to the product development team. The approach was applied to a class of flat mechanical products and microwave modules. Future work must investigate performing concurrent manufacturability evaluation and partner selection for comparing preliminary designs. Thus, the product development team can receive useful feedback even earlier in the product development process.

3.8. *Human factors*

The development of agile manufacturing systems involves many changes in culture and work practices. Many of these changes are related to human factors. According to Merton-Allen-Associates (1997): 'Human factors will not only play a vital role in accomplishing the technical and social objectives of agile manufacturing, but have an opportunity to participate in sharing the evolution of industry paradigms for the next century'. In this section, the papers found will be described.

Kidd (1994) in his book *Agile Manufacturing, Forging New Frontiers* made a contribution to the process of defining agile manufacturing. He proposed a conceptual framework, in which agility is achieved through the integration of organization, highly skilled and knowledgeable people and advanced technologies, to achieve cooperation and innovation to aid supplying our customers with high quality customized products. At the heart of the conceptual framework are four core concepts: (i) a strategy to become an agile manufacturing enterprise; (ii) a strategy to exploit agility to achieve competitive advantage; (iii) an integration of organization, people and technology into a coordinated, interdependent system which is the competitive weapon, and (iv) an interdisciplinary design methodology to achieve the integration of organization, people and technology. The author highlights the need to make better use of human skills, knowledge and experience and to exploit the power of modern computer-based technologies. To achieve all these goals we need skilled cooperative and motivated people, we need participation of people throughout the enterprise, in planning, designing and implementing new technologies and systems. Technical systems need to be designed, not just to meet economics and technical goals, but to satisfy organizational and human requirements. The aim should be to create an environment for the exercise of human skills, judgement, creativity, knowledge and ingenuity and to make full use of modern computer-based technologies.

Plonka (1997) examines the contribution that human factors practitioners can make to improve workforce capabilities in the lean and agile manufacturing environments. The article addresses the demands that lean and agile manufacturing initiatives will place on the current and emerging workforce to achieve increasing levels of quality and flexibility with lower costs and shorter product life cycles. The issues of worker selection, continuous skill development, workplace design, equipment maintenance, process improvement, mistake proofing, and process reconfiguration for new products are discussed from a human factors perspective. The article concludes that a new production system where human factors play a central role will be needed to help workforce members achieve greater success in meeting these demands.

Forsythe (1997) and Forsythe and Ashby (1996) summarize experiences from A-PRIMED (Agile Product Realization for Innovative Electro-Mechanical Devices) and many of the contributions of human factors/ergonomics to agile manufacturing obtained from the development of this project. A-PRIMED is an agile manufacturing pilot project, with the aim of creating a much faster design-to-production cycle for precision electro-mechanical devices. These papers summarize 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. More detailed discussion is offered for human factors related to the communications and information infrastructure essential to an organization making the transition from traditional to agile product development. In summary, despite initial work, significant development and research tackling issues of human factors concerned with agile manufacturing systems is needed.

3.9. *Business practices and processes*

One of the primary goals of an agile manufacturing enterprise is eventually to form a profitable organization. That means that business aspects must also be considered in the development of agile manufacturing systems. It is also of vital importance to evaluate how companies are evolving in the process to be agile enterprises. The first part of this section will be devoted to an evaluation of progress in four different countries. The second part is devoted to business issues.

3.9.1. *Progress evaluation in several countries*

In this subsection, agility progress in Korea, UK, Japan and Australia is reviewed. Table 14 presents a comparison, and in the following are the reviewed papers. Cho *et al*. (1996) address a few enabling technologies for agile manufacturing and also present various activities on agile manufacturing that are taking place in Korean academia and industry. Enabling technologies include STEP, concurrent engineering and centralized product models, virtual company, virtual manufacturing, a component-based hierarchical shop floor control system, groupware, just-in-time manufacturing, client–server computing technology, information and communication infrastructure, etc. Among the activities presented are the construction of a test-bed at Pohang University of Science and Technology through which customers send customer-designed product data, monitor the progress of manufacturing, and even perform quality control. Another activity presented was a small jean produc-

Author	Country	Purpose	Approach used
Cho *et al.* (1996)	Korea	Present enabling technologies and several activities showing how academia and industry, are evolving to agile manufacturing.	Present and analyse the major developments of representative industries and universities
Sharp *et al.* (1999)	UK	From survey data, they develop a conceptual model helpful to identify where companies are in their quest to become agile manufacturing organizations.	A questionnaire was developed and completed by best practitioners of manufacturing
Katayama and Bennett (1999)	Japan	Analysis based on survey data of how major Japanese companies are changing their strategies.	Survey administered to relatively large companies or business units.
Perry *et al.* (1999)	Australia	Describe the process of the Australian Quick Response program, which it is part of an agile manufacturing strategy; also identify key factors for successful outcomes from this program.	Workshops were held in this government funded programme. Cluster groups were formed which met for the purpose of mutual gain through improving their total effectiveness in servicing each other and the end consumer.

Table 14. Agility progress evaluation for specific countries.

tion company that developed a virtual textile manufacturing system in which the customers can rapidly order and receive a product. Another was a car service company that developed a telephone-aided car diagnosis and maintenance system through which a remotely located technician can investigate the customer's broken car through the phone line and identify the problems using a plug-into-the-phone remote diagnostic system. The last activity presented was the implementation of life cycle engineering using the product model of a TV set. The purpose of the activity was to collect product life cycle data and to design or improve materials, processes, assembly/disassembly, and managerial strategy. The results look promising.

Sharp *et al* (1999) present an explanation of key differentiators, conceptual differences and relationships between mass, lean and agile. After this explanation, the authors developed a conceptual model, where the key enablers/pillars are: competencies, virtual enterprise, rapid prototyping, concurrent engineering, multi-skilled and flexible people, continuous improvement, team working, change and risk management, information technology and empowering. In order to validate their conceptual model, a questionnaire was designed and completed by companies of the UK. Quantitative data were obtained and the authors state that the model will allow organizations to be able to assess their progress towards becoming agile organizations; although the results from the questionnaire were not statistically significant.

Katayama and Bennett (1999) identify critical problems between Japanese companies as well as their strategic directions and action programs. The results were obtained from a survey carried out during 1996. Among the conclusions drawn from the survey, the authors state that non-agility focused companies are starting to become aware of the importance of agility but have not yet linked the concept to concrete actions, while the agility-focused companies aim to reduce fixed costs and lower the break-even point rather than to concentrate on variable cost. Therefore, it should be possible to establish the hypothesis that companies are trying to realize their cost adaptability through agility enhancement activities.

Perry *et al.* (1999) outline the process that occurred as part of the Australian Quick Response program in the textiles, clothing and footwear industry. Agile manufacturing is complementary to Quick Response, a government funded programme. The authors developed a model of effective communication and multi-directional information flow, drawn from observations of the workshop processes and discussions with participants. This paper also identifies the key factors that led to the successful outcomes.

3.9.2. *Business issues*

The second part of this section will describe papers focused on business issues. Table 15 presents a comparison. The reviewed papers are the following. Meade and Rogers (1997) help to define and introduce the concept of agile business processes by linking determinants, dimensions, and characteristics of agility and business processes in a single systemic framework. They describe an evaluation model that combines quantitative and qualitative characteristics in hierarchical form to assist the decision maker in the configuration of agile business processes. This evaluation model is based on the Analytic Network Process (ANP) methodology for solving complex decisions; the Analytical Network Process (ANP) is a more general form of the Analytical Hierarchy Process (AHP). The model presented represents only one set of possible relationships. A variation in the Agile attribute enablers or Agile implementation enablers can also be made. Currently, depending on the actual com-

Author	Purpose	Approach
Meade and Rogers (1997)	Develop a model to help in the configuration of agile business processes	Analytic Network Process (ANP) methodology
Hoyt and Sarkis (1995)	Develop a framework of conditions related to management of engineering and scientific personnel	Analysis of economical trends, engineering personality and the relatinship with levels of motivation
Reid *et al.* (1996)	Develop a methodology for engineering and managing virtual enterprises	Development of three models
Gunasekaran (1998)	Definition of a conceptual framework for the development of an agile manufacturing system	Description of key concepts and enablers of agile manufacturing
Hoyt *et al.* (1997)	Demonstrate that classical organization theory and strategy research methods are useful for studying agile organizations	Data envelopment analysis (DEA) and Regression analysis

Table 15. Business issues. Comparison of papers.

pany using the model, the appropriate agile attribute enablers are specifically selected from a database.

Hoyt and Sarkis (1995) address the issues related to the management of engineering and scientific personnel. They review current literature to determine what research has been performed. Then they develop a commentary on the relevant issues and considerations involved in the management of these individuals as managers strive to achieve creativity along with economic results. First, they consider the effect of economic trends on technical employment and then look at how these trends influence the work environment. Next they consider the engineering personality and how it affects the individual's levels of motivation. Stress factors are discussed as a separate issue and they consider how job/task design and engineering career options influence stress levels, and motivation. Then they develop a framework of conditions that technical mangers must recognize and deal with in order to achieve creativity, innovation and productivity from their technical staff.

Reid *et al.* (1996) describe early results of research at the Agile Aerospace Manufacturing Research Center (AAMRC). A methodology for engineering and managing virtual enterprise has been discussed in terms of three concepts: a six-step virtual enterprise life cycle, enterprise processes organized into three management functions, and an organizational model known as integrated decentralization. The methodology specifically addresses the technical, cultural and managerial issues relating to the unique needs of the virtual enterprise, as cited in the literature and practice. Future work in this area will include completely integrating the three models to create a holistic vision and guiding infrastructure. Diagnostic assessment instruments and prescriptive templates will then be developed to enable firms to evaluate their current state, select a course of action, and create actionable plans to transform themselves.

Gunasekaran (1998) details the key concepts and enablers of agile manufacturing. The key enablers of agile manufacturing include: (i) virtual enterprise formation tools/metrics; (ii) physically distributed manufacturing architecture and teams; (iii) rapid partnership formation tools/metrics; (iv) concurrent engineering; (v) integrated product/production/business information system; (vi) rapid prototyping tools; and (vii) electronic commerce. He presents a framework that takes into account the customization and system integration with the help of business process redesign, legal issues, concurrent engineering, computer-integrated manufacturing, cost management, total quality management and information technology. The author concludes that the future manufacturing strategy for agile manufacturing enterprise should be in the following directions: (i) cooperative work among small and medium enterprises to utilize advantageously the capability of each company for mutually profitable projects; (ii) companies have to organize themselves as teams to take advantage of market opportunities; (iii) reengineering of the business process to facilitate an effective communication and integration of various partner-firms.

Hoyt *et al*. (1997) describe a scientific study that was performed to test the ability of five organizational processes to support agile performance. Planning, scanning, supply chain governance mechanisms, multi-skilled workers, and flexible manufacturing infrastructure. Sample companies, drawn from hostile-dynamic environments, are classified as successful or non-successful using Data Envelopment Analysis (DEA). These same companies are surveyed to measure the presence/absence of these enablers and a set of enabler scores was derived for each from a factor analysis. Classifications and enabler scores are then combined in a logistic regression to test the significance of each enabler to agile performance. This study demonstrates that classical organization theory and strategy research methods are useful for studying agile organizations.

This section first presented papers showing advances in agile manufacturing in four different countries. Table 14 summarizes these advances. In the second part, papers related to business/management issues were presented. Table 15 details the purpose of each paper and also the approach used.

4. Directions for further research

Agile manufacturing is a new strategy 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. More recent efforts suggest that agile companies are ones that have moved beyond tactical initiatives and have made fundamental changes in how they operate. At this point little research has been made considering the logistics process and also considering how to ensure quality among partners. In addition, we have found articles describing the characteristics of an agile manufacturing system, but few of them offer strategic plans to embark on these systems. No metrics have been developed in order to measure this transformation. Further investigation is needed in the application of the concept of agility in service industries.

In product and manufacturing systems design, efforts have been made in the compatibility of the systems, in the creation of standards, in the formulation of guidelines, but few efforts have been focused on the development of tools that make it possible for several designers to interact simultaneously, in 'real time', or asynchronously through a workflow management system. We need the formal development of guidelines or rules relating operational issues with the design of products. We also need formal development of tools for reconfigurability of manufacturing systems considering any possible combination of product similarity grade. Theories on rapid reconfiguration and self-organizing (modular) components need to be developed in response to mass customization needs of agile manufacturing.

In process planning, the use of generative process planning was touched upon. Given that agile manufacturing will facilitate sharing information between partners, the use of variant process planning must be exploited. The development of integrated systems, able to generate process planning using generative or variant or a mix of both, must be developed as well. In addition, development of architectures facilitating the link between existing systems and future developments is needed. Development of evaluation systems in order to compare alternative process plans is also demanded. Furthermore, as the production lots become smaller, the process planning and scheduling problems become more intertwined, in the sense that the ideal process to be selected at the process planning stage may be a temporary bottleneck at the shop floor level. Hence, a joint solution to both these problems must be developed.

In production planning, scheduling and control, there is still much work to accomplish. Agile manufacturing is in need of models for distribution of workload among partners that consider independent constraints for each partner. In addition, we need methods for the determination of a production schedule in a global/distributed environment, considering limitations and constraints of the constituent partners such as their own schedules, availability of production time, capacities, delays, etc. In addition, given that many uncertainties of the market can be present, we need this system to be able to re-schedule or recover from them. As part of this re-scheduling, the system must be able to re-select partners if this is the best choice for the new conditions. Research in production control systems and a quality management system for assurance of quality between partners is necessary. A production planning system able to evaluate all possible alternatives that can exist when an agile manufacturing enterprise is being formed, such as the creation of new facilities for this partnership, or the more common use of existing facilities, or a combination of both. An integrated production planning, scheduling and control system is also required.

In the facilities design area it is necessary to develop methodologies that consider the inclusion of external flows. These methodologies must also include and evaluate different options for input/output stations such as the location in a predefined place due to major technical and structural considerations or the searching for the best location in the layout. Future developments in facilities design must consider the analysis of additional aspects, such as dynamic layout generation, flow network design, aisle planning and/or detailed layout generation. This is necessary to further the development of methodologies able to solve the capacity/flow trade-off. It is also necessary to advance incorporation of flexibility and robustness measures under variations in design parameters, the analysis of the system design with objectives other than material transfer, and a deeper analysis of the quality of results obtained. We need the development of an integrated system of production planning and layout distribution, allowing the scheduling of items and lots taking advantage in real-time of the inter-workstations proximity attained by distributing the workstation of a given type throughout the layout. We also need clear specification of the rules that holographic layout design must follow for cell creation, and development of systems able to synchronize flow of materials, components and tools in order to achieve the potential benefits of holographic layouts. An additional extension for this type of layout design would be to relax the assumption of deterministic variables in the problem such as travel chart, and treat them as stochastic variables.

In facilities location, it is necessary to develop decision support systems that enable taking strategic decisions over a specific predetermined horizon planning. These systems must consider the dynamics of market demand.

In material handling and storage systems we require 'smart and faster storage systems' capable of handling large amounts of products that appear in an increasing variety of sizes, shapes, colours, etc. Modular material handling devices will also enable adaptability to changing product handling needs. In the 1996 International Material Handling Research Colloquium, the agility focus group discussion enumerated research issues on logistics, information and control systems, layout, storage and warehousing, and material handling equipment. The results of this group discussion are presented in Don-Taylor and Nagi (1996).

Given the vital role in an agile manufacturing enterprise, the information systems area has received a good amount of attention. Tremendous effort has been invested in this topic. However, development of security issues are still necessary. Additional development of systems able to adapt to the continuous change in technology promoted for the internet are necessary. Also, it must be evaluated whether the current private business net 'Factory America Network' is consistent with the requirements of agile manufacturing from openness as well as security points of view.

In supply chains, further research is necessary in the development of new metrics appropriated to evaluate the performance of partners in the agile supply chain. Game theoretic approaches in partner cooperation/competition need to be furthered.

In human factors, issues related to a multi-functional workforce and performance evaluation must be studied. Furthermore the nature of training and education in agile manufacturing should be defined. Suitable mathematical models need to be developed for the determination of the number/mix and cross-training of workers required in an agile environment.

In business practices and processes, a suitable engineering/cost accounting system should be developed able to provide in advance the accurate cost (quotation) of a product. Also, a better organizational structure for agile manufacturing systems should be developed based on the nature of information available and material flow. Evaluation studies of agility progress in different countries are also necessary.

5. Conclusions

Agile manufacturing systems are born as a solution to a society with an unpredictable and dynamic demand, and with a high degree of mass customization in its products. It is the strategy that many enterprises are adopting as a solution to the new market opportunities. Many articles have been written on this topic as we found more than 300. The greater part of these articles only explains the basics of agile manufacturing but a few have made contributions that provide elements to enable this new type of enterprise. In this survey we have reviewed recent work in agile manufacturing systems—73 papers were analysed. We proposed a classification scheme with nine major research areas: (i) product and manufacturing systems design; (ii) process planning; (iii) production planning, scheduling and control; (iv) facilities design and location; (v) material handling and storage systems; (vi) information systems; (vii) supply chain; (viii) human factors; (ix) business practices and processes.

For each one of these major areas, relevant papers were reviewed. For four out of these nine major areas a sub-classification was developed. We highlight that the information systems area was the research topic where the most amount of work has been performed. In addition, we observe that from 1995 until now a consistent number of papers about agile manufacturing systems has been published every year. We must emphasize that *International Journal of Production Research*, *IIE*

Transactions, and *International Journal of Production Economics* have been the journals where the majority of papers have been published on this topic. In addition, for each one of the nine major research topics, we have identified areas where further research is needed.

We hope that this paper reinforces the ongoing research, provides a broad view of the current status in agile manufacturing research, and offers potential directions for the development and operation of agile manufacturing enterprises.

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References

Aoyama, M., 1998, A web-based agile software development. *IEEE Software*, **15**(6), 56–65.

Candadai, A., Herrmann, J. W. and Minis, I., 1995, A group technology-based variant approach for agile manufacturing. *Concurrent Product and Process Engineering*. *ASME*, **85**, 289–305.

Canel, C. and Khumawala, B. M., 1997, Multi-period international facilities location: an algorithm and application. *International Journal of Production Research*, **35**(7), 1891–1910.

Cheng, K., Harrison, D. K. and Pan, P. Y., 1998, Implementation of agile manufacturing—an AI and internet based approach. *Journal of Materials Processing Technology*, **76**(1), 96–101.

Cho, H., Jung, M. and Kim, M., 1996, Enabling technologies of agile manufacturing and its related activities in Korea. *Computers and Industrial Engineering*, **30**(3), 323–334.

Don-Taylor, G., 1997, Design for global manufacturing and assembly. *IIE Transactions*, **29**(7), 585–597.

Don-Taylor, G. and Nagi, R., 1996, Agile manufacturing in material handling and logistics: Implications and a research agenda. *Progress in Material Handling Research*, Ann Arbor, MI, pp. 9–13.

Dove, R., 1995, Design principles for agile production. *Production*, **107**(12), 16–18.

Feng, S. C. and Zhang, C. C., 1998, A modular architecture for rapid development of CAPP systems for agile manufacturing. *IIE Transactions*, **30**, 893–903.

Forsythe, C., 1997, Human factors in agile manufacturing: A brief overview with emphasis on communications and information infrastructure. *Human Factors and Ergonomics in Manufacturing*, **7**(1), 3–10.

Forsythe, C. and Ashby, M. R., 1996, Human factors in agile manufacturing. *Ergonomics in Design*, **4**(1), 15–21.

Goldman, S. L., Nagel, R. N. and Preiss, K., 1994, *Agile Competitors and Virtual Organizations: Strategies for Enriching the Customer* (New York: Van Nostrand Reinhold).

Govindaraj, T., 1997, A distributed information system to assist engineering designers. *IERC Proceedings 1997, 6th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 537–542.

Gunasekaran, A., 1998, Agile manufacturing: enablers and an implementation framework. *International Journal of Production Research*, **36**(5), 1223–1247.

Gupta, P. and Nagi, R., 1995, Flexible optimization framework for partner selection in agile manufacturing. *IERC Proceedings 1995, 4th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 691–700.

GUPTA, P. and NAGI, R., 1996, Process-partner selection in agile manufacturing using linguistic decision making. Department of Industrial Engineering. State University of New York at Buffalo.

GUPTA, S., HERRMANN, J. W., LAM, G. and MINIS, I., 1997, Automated high level process planning to aid design for agile manufacturing. *IERC Proceedings 1997, 6th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 1–19.

HARDWICH, M., SPOONER, D. L., RANDO, T. and MORRIS, K. C., 1996, Sharing manufacturing information in virtual enterprises. *Communications of the ACM*, **39**(2), 46–54.

HAUG, P., 1992, International location and production transfer model for high technology multinational enterprises. *International Journal of Production Research*, **30**(3), 559–572.

HE, D. W. and KUSIAK, A., 1994, Design of products and assembly systems for agility. Manufacturing Science and Engineering, 1994. *ASME International Mechanical Engineering Congress and Exposition*, New York, pp. 29–34.

HE, D. W. and KUSIAK, A., 1995, The delayed product differentiation strategy in agile manufacturing. *IERC Proceedings 1995, 4th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 701–708.

HE, D. W. and KUSIAK, A., 1996, Production planning and scheduling in virtual manufacturing. *IERC Proceedings 1996, 5th Annual Industrial Engineering Research Conference*. pp. 491–496.

HERRMANN, J. W., MINIS, I. and RAMACHANDRAN, V., 1995, Information models for partner selection in agile manufacturing. *Engineering Data Management and Emerging Technologies*. Volume 7 New York, USA, pp. 75–91.

HERRMANN, J. W. and MINIS, I., 1996, Design evaluation and partner selection for agile manufacturing. Institute for Systems Research and Department of Mechanical Engineering. University of Maryland, College Park.

HOYT, J., 1995, Strategic and economic issues of supply chain alliances for agile organizations. *IERC Proceedings 1995, 4th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 49–56.

HOYT, J., HUQ, F. and LILES, D. H., 1997, Design of a study to test the statistical significance of five enablers of agile manufacturing organizations. *IERC Proceedings 1997, 6th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 966–971.

HOYT, J. and SARKIS, J., 1995, Strategic issues in the management and motivation of engineers and scientific personnel in agile organizations. *IERC Proceedings 1995, 4th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 682–690.

IRANI, S. A., CAVALIER, T. M. and COHEN, P. H., 1993, Virtual manufacturing cells: Exploiting layout design and intercell flows for the machine sharing problem. *International Journal of Production Research*, **31**(4), 791–810.

IYER, S. and NAGI, R., 1994, Identification of similar parts in agile manufacturing. *Concurrent Product Design. ASME*, **74**, 87–96.

IYER, S. and NAGI, R., 1997, Automated retrieval and ranking of similar parts in agile manufacturing. *IIE Transactions*, **29**(10), 859–876.

JAIN, S., 1995, Virtual factory framework: a key enabler for agile manufacturing. INRIA/IEEE Symposium on Emerging Technologies and Factory Automation: *Proceedings, EFTA '95*, Paris, France (Los Alamitos, CA: IEEE Press), pp. 247–258.

JOHNSON, M. E. and REID, R. L., 1997, The design of a strategic information system. *IERC Proceedings 1997, 6th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 525–530.

JUNG, M., CHUNG, M. K. and CHO, H., 1996, Architectural requirements for rapid development of agile manufacturing systems. *Computers & Industrial Engineering*, **31**, 551–554.

KATAYAMA, H. and BENNETT, D., 1999, Agility, adaptability and leanness: a comparison of concepts and a study of practice. *International Journal of Production Economics*, **60**, 43–51.

KIDD, P. T., 1994, *Agile Manufacturing. Forging New Frontiers* (Reading, MA: Addison-Wesley).

KOONCE, D., DHAMIJA, D. and JUDD, R., 1997, An integrated model for manufacturing information exchange. *IERC Proceedings 1997, 6th Annual Industrial Engineering Research Conference*. Norcross, GA, USA, pp. 531–536.

KUSIAK, A., 1990, *Intelligent Manufacturing Systems* (Englewood Cliffs, NJ: Prentice Hall).

Kusiak, A. and Feng, C.-X., 1994, Design of products for an agile manufacturing environment. *Computers in Engineering, 14th ASME International Computers in Engineering Conference and Exposition*. New York, USA, pp. 413–420.

Kusiak, A. and He, D. W., 1997, Design for agile assembly: an operational perspective. *International Journal of Production Research*, **35**(1), 157–178.

Lee, G. H., 1997, Reconfigurability consideration design of components and manufacturing systems. *International Journal of Advanced Manufacturing Technology*, **13**(5), 376–386.

Lee, G. H., 1998, Designs of components and manufacturing systems for agile manufacturing. *International Journal of Production Research*, **36**(4), 1023–1044.

Liu, C. M., Wang, M. J. and Pang, Y.-S., 1994, A multiple criteria linguistic decision model (mcldm) for human decision making. *European Journal of Operational Research*, **76**, 466–485.

Mason-Jones, R. and Towill, D. R., 1999, Total cycle time compression and the agile supply chain. *International Journal of Production Economics*, **62**, 61–73.

Meade, L. M. and Rogers, K. J., 1997, A method for analyzing agility alternative for business processes. *IERC Proceedings 1997, 6th Annual Industrial Engineering Research Conference*. Norcross, GA, pp. 960–965.

Meller, R. D. and Mungwattana, A., 1997, Multi-shuttle automated storage/retrieval systems. *IIE Transactions*, **29**, 925–938.

Merton-Allen-Associates, 1997, Agile manufacturing: the human factors. *Innovator's Digest*.

Mills, J. J., 1995, An integrated infrastructure for agile manufacturing. *Manufacturing Science and Engineering, 1995 ASME International Mechanical Engineering Congress and Exposition*, San Francisco, CA, pp. 1037–1047.

Minis, I., Herrmann, J. W., Lam, G. and Lin, E., 1999, A generative approach for concurrent manufacturability evaluation and subcontractor selection. *Journal of Manufacturing Systems*, **18**(6), 383–395.

Montreuil, B., Venkatadri, U. and Lefrancois, P., 1991, Holographic layout of manufacturing systems. *19th IIE Systems Integration Conference. Systems Integration for Rapid Product Development and Manufacturing*, Orlando, Florida, USA, pp. 1–13.

Montreuil, B., Venkatadri, U. and Rardin, R. L., 1999, Fractal layout organization for job shop environments. *International Journal of Production Research*, **37**(3), 501–521.

Nagel, R. N. and Dove, R., 1991, *21st Century Manufacturing Enterprise Strategy: An Industry-lead View* Volume 1. (Bethlehem, PA: Iacocca Institute).

Naylor, J. B., Naim, M. M. and Berry, D., 1999, Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain. *International Journal of Production Economics*, **62**, 107–118.

Olsen, K. A. and Saetre, P., 1997, Managing product variability by virtual products. *International Journal of Production Research*, **35**(8), 2093–2107.

Pant, S., Rattner, L. and Hsu, C., 1994, Manufacturing information integration using a reference model. *International Journal of Operations and Production Management*, **14**(11), 52–72.

Perry, M., Sohal, A. S. and Rumpf, P., 1999, Quick response supply chain alliances in the Australian textiles, clothing and footwear industry. *International Journal of Production Economics*, **62**, 119–132.

Plonka, F. E., 1997, Developing a lean and agile work force. *International Journal of Human Factors in Manufacturing*, **7**(1), 11–20.

Pradhan, S. S. and Huang, W. V., 1998, Virtual manufacturing information system using JavaTM and JDBCTM. *Computers & Industrial Engineering*, **35**(1), 255–258.

Quinn, R. d., Causey, G. C., Merat, F. L., Sargent, D. M., Barendt, N. A., Newman, W. S., Velasco, V. B., Podgurski, A., Jo, J.-Y., Sterling, L. S. and Kim, Y., 1997, An agile manufacturing workcell design. *IIE Transactions*, **29**(10), 901-909.

Reid, R. L., Rogers, K. J., Johnson, M. E. and Liles, D. H., 1996, Engineering the virtual enterprise. *IERC Proceedings 1996, 5th Annual Industrial Engineering Research Conference*. pp. 485–490.

Richards, C. W., 1996, Agile manufacturing: Beyond lean? *Production and Inventory Management Journal*, **37**(2), 60–64.

Sarmiento, A. M., 2000, *An integrated production-logistics approach to partner-chain design in agile manufacturing*. PhD Thesis, Department of Industrial Engineering, State University of New York at Bufallo.

Sarmiento, A. M. and Nagi, R., 1998, Partnership selection for virtual enterprises from organizational webs. *IERC Proceedings 1998, 7th Annual Industrial Engineering Research Conference*. Banff, Alberta, Canada, pp. 1–9.

Sarmiento, A. M. and Nagi, R., 1999, A review of integrated analysis of production-distribution systems. *IIE Transactions Special Issue on Manufacturing Logistics*, **11**(3), 1061–1074.

Sharp, J. M., Irani, Z. and Desai, S., 1999, Working towards agile manufacturing in the UK industry. *International Journal of Production Economics*, **62**, 155–169.

Sheridan, J. H., 1993, Agile manufacturing: Stepping beyond lean production. *Industry Week*, **242**(8), 30–46.

Smith, R. L. and Wolfe, P. M., 1995, Implications of client/server systems on the virtual corporation. *Computers & Industrial Engineering*, **29**(1), 99–102.

Song, L. and Nagi, R., 1996, An integrated information framework for agile manufacturing. *IERC Proceedings 1996, 5th Annual Industrial Engineering Research Conference*, pp. 568–573.

Song, L. and Nagi, R., 1997, Design and implementation of a virtual information system for agile manufacturing. *IIE Transactions*, **20**(10), 839–857.

Strader, T. J., Lin, F.-R. and Shaw, M. J., 1998, Information infrastructure for electronic virtual organization management. *Decision Support Systems*, **23**(1), 75–94.

Struebing, L., 1995, New approach to agile manufacturing. *Quality Progress*, **28**(12), 18–19.

Syam, S. S., 1997, Model for the capacitated p-facility location problem in global environments. *Computers and Operations Research*, **24**(11), 1005–1016.

Talluri, S., Baker, R. C. and Sarkis, J., 1999, A framework for designing efficient value chain networks. *International Journal of Production Economics*, **62**, 133–144.

Tu, Y., 1997, Production planning and control in a virtual one of a kind production company. *Computers in Industry*, **34**(3), 271–283.

Veeramani, D. and Joshi, P., 1997, Methodologies for rapid and effective response to request for quotation (RFQs). *IIE Transactions*, **29**, 825–838.

Venkatadri, U., Rardin, R. L. and Montreuil, B., 1996, Facility organization and layout design: an experimental comparison for job shops. Travel document 96-27 Centre SORCHIER, Faculte des Sciences de l'administration, University Laval and School of Industrial Engineering, Purdue University.

Venkatadri, U., Rardin, R. L. and Montreuil, B., 1997, A design methodology for fractal layout organization. *IIE Transactions*, **29**, 911–924.

Wang, Z. Y., Rajurkar, K. P. and Kapoor, A., 1996, Architecture for agile manufacturing and its interface with computer integrated manufacturing. *Journal of Materials Processing Technology*, **61**(1), 99–103.

Weng, Z. K., 1999, Risk pooling over demand uncertainty in the presence of product modularity. *International Journal of Production Economics*, **62**, 75–85.

Weston, R. H., 1998, Integrational infrastructure requirements for agile manufacturing systems. *Proceedings of the Institution of Mechanical Engineers Part B, Journal of Engineering Manufacture* Volume 212, pp. 423–437.

Wiebe, E. N., 1997, Adding agility to CAD: Integrating product data management tools into an organization. *Human Factors and Ergonomics in Manufacturing*, **7**(1), 21–35.

Wong, C.-C., Chalermdamrichai, V. and Veeramani, D., 1996, Quester: A computer-integrated system for virtual shopping through the internet. *IERC Proceedings 1996, 5th Annual Industrial Engineering Research Conference*. pp. 758–763.

Zhou, Q. and Besant, C. B., 1999, Information management in production planning for a virtual enterprise. *International Journal of Production Research*, **37**(1), 207–218.

Zhou, Q., Souben, P. and Besant, C. B., 1998, Information management system for production planning in virtual enterprises. *Computers & Industrial Engineering*, **35**(1), 153–156.