Applications of agent-based systems in intelligent manufacturing: An updated review

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Abstract

Agent technology has been recognized as a promising paradigm for next generation manufacturing systems. Researchers have attempted to apply agent technology to manufacturing enterprise integration, enterprise collaboration (including supply chain management and virtual enterprises), manufacturing process planning and scheduling, shop floor control, and to holonic manufacturing as an implementation methodology. This paper provides an update review on the recent achievements in these areas, and discusses some key issues in implementing agent-based manufacturing systems such as agent encapsulation, agent organization, agent coordination and negotiation, system dynamics, learning, optimization, security and privacy, tools and standards.

Keywords: Agents; Multi-agent systems; Intelligent manufacturing; Distributed manufacturing systems

1. Introduction

Global competition and rapidly changing customer requirements are forcing major changes in the production styles and configuration of manufacturing organizations. Increasingly, traditional centralized and sequential manufacturing process planning, scheduling, and control mechanisms are being found insufficiently flexible to respond to changing production styles and high-mix low-volume production environments. The traditional approaches limit the expandability and reconfigurability of the manufacturing systems. The centralized hierarchical organization may also result in much of the system being shut down by a single point of failure, as well as plan fragility and increased response overheads. Agent technology provides a natural way to address such problems, and to design and implement efficient distributed intelligent manufacturing systems.

The concept of a software agent can be traced back to Hewitt’s Actor Model aiming at solving large problems [55]. Recently, agent technology has been considered as an important approach for developing industrial distributed systems [60,61]. It has particularly been recognized as a promising paradigm for next generation manufacturing systems [122,123]. Researchers have attempted to apply agent technology to manufacturing enterprise integration, enterprise collaboration (including supply chain management and virtual enterprises), manufacturing process planning and scheduling, shop floor control, and to holonic manufacturing as an implementation methodology. Our previous survey paper [122] provides a review of the literature until 1998. This paper provides an update review on the recent achievements in these areas, and discusses some key issues in implementing agent-based intelligent manufacturing systems.
2. Overview

2.1. Requirements for next generation manufacturing systems

The manufacturing enterprises of the 21st century are in an environment where markets are frequently shifting, new technologies are continuously emerging, and competition is globally increasing. Manufacturing strategies should therefore shift to support global competitiveness, new product innovation and customization, and rapid market responsiveness. The next generation manufacturing systems will thus be more strongly time-oriented (or highly responsive), while still focusing on cost and quality. Such manufacturing systems will need to satisfy a number of fundamental requirements:

R1. Full integration of heterogeneous software and hardware systems within an enterprise, a virtual enterprise, or across a supply chain;
R2. Open system architecture to accommodate new subsystems (software or hardware) or dismantle existing subsystems “on the fly”;
R3. Efficient and effective communication and cooperation among departments within an enterprise and among enterprises;
R4. Embodiment of human factors into manufacturing systems;
R5. Quick response to external order changes and unexpected disturbances from both internal and external manufacturing environments;
R6. Fault tolerance both at the system level and at the subsystem level so as to detect and recover from system failures and minimize their impacts on the working environment.

2.2. Agent-based approaches for intelligent manufacturing

Techniques from Artificial Intelligence have already been used in Intelligent Manufacturing for more than two decades. However, the recent developments in multi-agent systems have brought new and interesting possibilities [149,102,61,123]. Therefore, researchers have been trying to apply agent technology to manufacturing enterprise integration, enterprise collaboration, manufacturing process planning, scheduling and shop floor control, materials handling and inventory management, as well as to the implementation of new kinds of manufacturing systems such as Holonic Manufacturing Systems [33].

In distributed intelligent manufacturing systems, agents can be applied and implemented in different ways:

- Agents can be used to encapsulate manufacturing activities or wrap legacy software systems in an open, distributed intelligent environment using a functional decomposition approach (see Section 4.1 for details). Examples of such functional agents include order processing, product design, engineering analysis, process planning, production planning and scheduling, simulation, and execution [42,107,7,84,125,1,155,116]. Such an agent-based encapsulation and integration approach can significantly facilitate the integration of heterogeneous software and hardware systems, particularly plug-and-play kind of integration. It can also enhance communication and cooperation among departments within an enterprise and among enterprises. Therefore, it well addresses the first three requirements mentioned in Section 2.1.

- Agents can be implemented to represent physical manufacturing resources (e.g., machines, robots, tools, fixtures, AGVs, and operators) or aggregations of resources (e.g., cells, production lines, and shop floors) as well as products, parts, and operations [21,103,83,124,78,140,145]. In fact, this addresses the last three requirements discussed above. Human operators represented by software agents and interacted with agents through user interfaces will cooperate with manufacturing resources (also represented by software agents), particularly those intelligent machines to complete manufacturing tasks more effectively. Different from centralized approaches, agent-based manufacturing scheduling and control system can respond quickly to dynamic changes and disturbances (either internal or external) through local decision making. This approach also provides much better fault tolerance than traditional approaches because of its loosely coupled system architecture and the autonomy of individual resource agents. By using this approach, manufacturing enterprises will be able to reduce their response time to market demands and therefore to win in a globally competitive market.

- Agents can be deployed to represent negotiation partners, either physical plants or virtual players, such as master plants, virtual partners, or dynamic consortia [12,76,116,53] to facilitate enterprise collaboration. This also addresses the first and third requirements.

- Agents can also be used to implement some special services in agent-based manufacturing systems, such as Agent Name Server in CIIMPLEX [107] and Enterprise Mediator in MetaMorph [82,125] for providing registration and administration services; Facilitators in PACT [31] and CIIMPLEX [107] and Mediators in MetaMorph for facilitating communication, cooperation and coordination among other agents; Database Agents [73] and Information Agents [42,84,83,140] for providing information management services.

In Holonic Manufacturing Systems (HMS), software agents are used to implement holons which are software and hardware entities [33,81]. A good discussion on agent technology for Holonic Manufacturing Systems can be found in [19]. More details are presented in Section 3.5.
2.3. Agents, autonomous agents and agent-based systems

Under the context of collaborative intelligent manufacturing, we define an agent as a software system that communicates and cooperates with other software systems to solve a complex problem that is beyond the capability of each individual software system. This is compatible with Jennings and Wooldridge’s definition [61] adopted in our previous survey paper [122]: “an agent is a computer system situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives.” An autonomous agent should be able to act without the direct intervention of human beings or other agents, and should have control over its own actions and internal states. And an “agent-based system” means a system in which the key abstraction used is that of an agent. It is a loosely coupled network of problem solvers that work together to solve problems that are beyond their individual capabilities. Various interesting features of agents have been proposed and defined in the literature. However, some of them are more important and useful in agent-based manufacturing, e.g., autonomous, cooperative, proactive, and adaptive [123].

3. Agent-based systems for intelligent manufacturing

In this section we review some related projects, in a tabular format, giving for each item where available: project name, working group (in reference citation format), application domains and main features. The projects are classified into five categories: (1) enterprise integration; (2) enterprise collaboration (including supply chain management, virtual enterprises and other collaboration types); (3) manufacturing process planning and scheduling; (4) manufacturing shop floor control; and (5) Holonic Manufacturing Systems.

3.1. Enterprise integration

Enterprise integration means that each unit of the organization will have access to the information relevant to its tasks and will understand how its actions will impact other parts of the organization thereby enabling it to choose alternatives that optimize the organization’s goals [123]. For a manufacturing enterprise to win in a globally competitive market, it must own and maintain an integrated information system in order to manage all its business, administrative, engineering and operational affairs, including marketing, finance, purchasing, sales, product design, process planning, scheduling, process control, and quality assurance.

However, enterprise integration is still a very difficult problem for most manufacturing enterprises, particularly small and medium sized enterprises (SMEs). Isolated, heterogeneous and even obsolete legacy systems are required to be improved and integrated rather than discarded for many reasons. Limited resources, tight budget, operation consistency, and peer recognition are major factors among them.

Many researchers have been probing into solutions for enterprise integration and some reached the conclusion that the agent technology provides a nature way to realize enterprise integration. Agent-based enterprise integration has been a very active research area recently [93,29,78,157,53,99]. In addition to significant academic researches, some projects have attracted active industrial participation and developed industrial applications [107,78,157]. In most projects, software agents are used to encapsulate existing legacy software systems using various middleware approaches.

Table 1 summarizes some projects on agent-based enterprise integration.

3.2. Enterprise collaboration

Coexistence of competition and cooperation is a dichotomy governing today’s enterprises [134]. Enterprises collaborate vertically along a supply chain and horizontally among peers (even competitors) becomes more and more significant for enterprises to survive in the increasingly competitive global market. Jagdev and Thoben [59] recognize three types of enterprise collaborations: supply chain, extended enterprise and virtual enterprise (VE).

An extended enterprise can be looked upon as a tightly coupled, highly integrated enterprise collaboration form whose management issues are largely enriched beyond the traditional ERP/MRP systems, such as customer relationship management, sales chain management, high-level executive decision support, and new business development. Extended enterprise, no matter how advanced, is implemented by using the same technologies as enterprise integration.

A supply chain is a world-wide network of suppliers, factories, warehouses, distribution centers and retailers through which raw materials are acquired, transformed and delivered to customers [42]. Improving the performance of supply chain management is a key strategy to enhance the enterprise’s competitiveness and profitability. Consequently, enterprises are moving towards open architectures for integrating their activities with those of their suppliers, customers and partners within supply chain networks. A supply chain network also, in general, involves heterogeneous environments. Agent-based approaches provide a flexible and dynamic way of supply chain organization, planning and operations. Fox et al. [42] may have been the first to propose organizing the supply chain as a network of cooperating intelligent agents. A similar proposal has been made by Swaminathan et al. [135] using a multi-agent framework for modeling supply chain dynamics. In the supply chain library proposed by Swaminathan et al. [135], two categories of elements are distinguished: structural elements and control elements, where structural
elements refer to the production entities (retailers, distribution centers, plants, suppliers, transportations) and control elements are those helping in coordinating flow of products by efficient message interactions (inventory, demand, supply, flow and information controls). MetaMorph II [125] used a hybrid agent-based mediator-centric architecture to integrate partners, suppliers and customers dynamically with the lead enterprise through their respective mediators within a supply chain network via the Internet and Intranets. In MetaMorph II, agents are used to represent manufacturing resources (such machines and tools) and parts, to encapsulate existing software systems, to function as system/subsystem coordinators (mediators), and to perform one or more supply chain functions. MASCOT (Multi-Agent Supply Chain Coordination Tool) [116] introduced a reconfigurable, multi-level, agent-based decision support environment for dynamic supply chain management. The selection of supply chain partners is performed dynamically through lateral and vertical coordination of multiple agents and the support of a blackboard structure and mix-initiative decision making strategies. Also, some researchers have proposed applying mobile agent technology to enterprise integration and supply chain management [16,98,154,51,70].

<table>
<thead>
<tr>
<th>Project</th>
<th>References/organization</th>
<th>Application domains</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABMA</td>
<td>Budenske et al. [17], Architecture Tech. Co.</td>
<td>Enterprise integration</td>
<td>Middleware architecture</td>
</tr>
<tr>
<td>ATP</td>
<td>NIST [93], NIST</td>
<td>Agile manufacturing</td>
<td>Plug-and-play framework</td>
</tr>
<tr>
<td>CIIMPLEX</td>
<td>Peng et al. [107], UMBC</td>
<td>Enterprise integration</td>
<td>Service agents (Name Server, Facilitator Agent, Gateway Agent)</td>
</tr>
<tr>
<td>CLAIM</td>
<td>Malkoun and Kendall [79], RMIT, Taiwan</td>
<td>Enterprise integration</td>
<td>Methodology for enterprise integration using agents</td>
</tr>
<tr>
<td>GMPP</td>
<td>Yu and Huang [156], NTU, Taiwan</td>
<td>Enterprise integration</td>
<td>Model the order fulfillment process of the foundry fab using GMPP (General Message-Passing Platform)</td>
</tr>
<tr>
<td>IA framework</td>
<td>Pan and Tenenbaum [96], Stanford</td>
<td>Enterprise integration</td>
<td>Large number of computerized assistants, known as Intelligent Agents (IAs)</td>
</tr>
<tr>
<td>JACKAL</td>
<td>Cost et al. [29], UMBC, USA</td>
<td>Enterprise planning and execution</td>
<td>JACKAL is a Java-based multi-agent development platform. Cost et al. demonstrated how JACKAL supports intelligent integration of enterprise planning and execution through a simple business scenario</td>
</tr>
<tr>
<td>KRAFT</td>
<td>Gray et al. [49], KRAFT consortium</td>
<td>Transformation and reuse of knowledge</td>
<td>Mediators as knowledge brokers</td>
</tr>
<tr>
<td>LekiNET</td>
<td>Yen and Wu [155], UHK, China; UBC, Canada</td>
<td>Scheduling systems integration</td>
<td>Existing manufacturing scheduling systems are wrapped as Internet scheduling agents; Vickrey auction for agent coordination</td>
</tr>
<tr>
<td>MAKE-IT</td>
<td>Sacile et al. [114], University of Genova, Italy</td>
<td>Enterprise information integration</td>
<td>Structural communication modeling based on XML and MSMQ; knowledge modeling based on CLIPS system shell “if-then” rule-based tasks</td>
</tr>
<tr>
<td>MaMA-S</td>
<td>Galland et al. [44], UTBM, France</td>
<td>Integration of distributed simulation systems</td>
<td>A methodological approach for the creation of simulation models of complex and distributed systems</td>
</tr>
<tr>
<td>MetaMorph I</td>
<td>Maturana et al. [82], U of Calgary</td>
<td>Intelligent manufacturing</td>
<td>Mediator-centric architecture; dynamic clustering and cloning; learning</td>
</tr>
<tr>
<td>POMAESS framework</td>
<td>Yu et al. [157], CRAN, France; HUST, China</td>
<td>E-maintenance</td>
<td>Integrating remote maintenance processes and experts for maintenance decision-making; case-based reasoning; valve maintenance for water level control</td>
</tr>
<tr>
<td></td>
<td>Fleury et al. [39], Manufacturing system optimization</td>
<td>“Triple coupling” of multi-agent techniques, simulated annealing, and simulation</td>
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<tr>
<td></td>
<td>Hao et al. [53], NRC-IMTI, Canada</td>
<td>Enterprise manufacturing management integration</td>
<td>An internet enabled framework integrating manufacturing management issues on inter-enterprise, enterprise and shop floor levels</td>
</tr>
<tr>
<td></td>
<td>Jia et al. [64], NUS, Singapore</td>
<td>Product development and manufacturing</td>
<td>One central managing agent that supervises five distributed functional agents for product development and manufacturing process</td>
</tr>
<tr>
<td></td>
<td>Kim et al. [66], IIT and RPI, USA</td>
<td>Warehouse planning</td>
<td>Hybrid agent-based scheduling and control; warehouse order picking optimization; GA and mathematics models are used for higher level optimization (agents)</td>
</tr>
<tr>
<td></td>
<td>Lu and Yih [78], Purdue University, USA</td>
<td>Production control</td>
<td>Elevator production control; dynamic priority adjustment of sub-assemblies; simple index values for information exchange</td>
</tr>
<tr>
<td></td>
<td>Pancerella et al. [97], Sandia Lab</td>
<td>Agile manufacturing</td>
<td>An agent defined as an autonomous, encapsulated software component</td>
</tr>
<tr>
<td></td>
<td>Wanderli et al. [152], ETH Zentrum</td>
<td>CIM systems</td>
<td>Database agents for CIM systems</td>
</tr>
<tr>
<td></td>
<td>Yan et al. [154], Leipzig</td>
<td>Project management</td>
<td>Using mobile agents</td>
</tr>
</tbody>
</table>
Information and Communication Technologies (ICT) are the enabling technologies that have stimulated the emergence and evolution of various enterprise collaborations. More specifically, the recent VE type of enterprise collaboration has the highest demand for sophisticated ICT technologies. A virtual enterprise can be defined as “a network of independent organizations that jointly form an entity committed to provide a product or service” [59,22]. Thus, from the customer’s perspective, as far as that product/service is concerned, these independent organizations, for all practical and operational purposes, are virtually acting as a single entity/enterprise. A detailed discussion on applications of agent technology to Virtual Enterprise can be found in [80].

Table 2 summarizes some projects in agent-based enterprise collaboration.

### 3.3. Manufacturing process planning and scheduling

Manufacturing processing planning is the process of selecting and sequencing manufacturing processes such that they achieve one or more goals and satisfy a set of domain constraints. Manufacturing scheduling is the process of selecting among alternative plans and assigning manufacturing resources and time to the set of manufacturing processes in the plan. It is, in fact, an optimization process by which limited manufacturing resources are allocated over time among parallel and sequential activities. With the manufacturing globalization, such an optimization process is becoming more and more important for manufacturing enterprises to increase their productivity and profitability through greater shop floor agility, and survive in a globally competitive market [127].

Most scheduling problems are considered to be NP-hard, i.e., it is impossible to find an optimal solution without the use of an essentially enumerative algorithm and the computation time increases exponentially with problem size. Manufacturing scheduling is one of most difficult problems in all kinds of scheduling problems. It becomes more complex when considering multiple manufacturing resources, integration of process planning and scheduling, and dynamic situations in shop floors [127].

Within the past two decades, researchers have applied agent technology in attempts to resolve the manufacturing process planning and scheduling problems [123,129]. In fact, this represents one of the most active research topics on agent-based manufacturing. Table 3 presents a summary of some projects using agent technology for manufacturing process planning and scheduling.

Recent interesting research work in this area includes market-based negotiation protocols [83,71,47], agent-based integration of manufacturing process planning and scheduling [129], combination of agent-based approaches with traditional scheduling techniques such as heuristic search methods, performance matrix, Perti Nets, Genetic Algorithms, Neural Networks, and Simulated Annealing. [127,128,30].

### 3.4. Manufacturing shop floor control

Manufacturing shop floor control relates to strategies and algorithms for operating a manufacturing plant, taking into account both the present and past observed states of the manufacturing plant, as well as the demand from the market. The manufacturing control problem can be considered at two levels: low- and high-level. At the low-level, the individual manufacturing resources are to be controlled to deliver unit-processes expected by the high-level control functions. High-level manufacturing control is concerned with coordinating the available manufacturing resources to make the desired numbers of types of products. Agent technology is usually applied to high-level manufacturing control, but can also be applied to the lower level [13,146].

Shaw may have been the first to propose using agents in manufacturing scheduling and factory control. He proposed that a manufacturing cell can subcontract work to other cells through a bidding mechanism [119,120]. YAMS [100] was another of the earliest agent-based manufacturing systems, wherein each factory and factory component is represented by an agent. Each agent has a collection of plans, representing its capabilities. The Contract Net [130] is used for inter-agent negotiation. Most recent projects in this area still use the same idea. Table 4 presents a summary of these related projects.

In most agent-based approaches proposed for low-level shop floor control, an agent is to represent a physical manufacturing device (cell, machine, robot, AGV, tool etc.). These agents form a heterogeneous or hybrid architecture to negotiate laterally or vertically (through a mediator or coordinator) using coordination protocols by message passing. Most systems apply the Contract Net or its variations [4,103,14]. Some others use the Market-like negotiation [20,73,138]. However, in the area of real time scheduling and control of low-level devices, Wallace [144] is very conservative about the performance of agent-based approaches because of the heavy burden of message passing. His experimental comparisons between an agent-based controller and traditional simulation-based controller for AGV flow control indicated a low performance of the former, even though a specialized coordination protocol that aims for minimizing the number of messaging passing between agents was employed. So Wallace believed that the applicability of agent-based coordination in real time control environment still needs to be validated and special negotiation protocols that can promote real-time performance need to be exploited.

### 3.5. Holonic Manufacturing Systems (HMS)

The HMS concept was proposed in 1994 by the HMS consortium as a test case under the international Intelligent Manufacturing Systems Research Program (http://www.ims.org/). “Holon” is a word coined by combining “holos” (the whole) and “on” (a particle) following Koestler [67]. A holon is defined by the HMS consortium as “an
autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects” [143]. A holon can be part of another holon. Another important concept is the “holarchy” that is defined as “a system of holons which can cooperate to achieve a goal or objective”.

### Table 2
Summary of projects on agent-based enterprise collaboration

<table>
<thead>
<tr>
<th>Project</th>
<th>References/organization</th>
<th>Application domains</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADE</td>
<td>Mehra and Nissen [86], Gensym Co.</td>
<td>Supply chain</td>
<td>Using delegation-based event handling similar to JavaBeans</td>
</tr>
<tr>
<td>AGENT-OPT</td>
<td>Chan and Lee [23], KAIST, Korea</td>
<td>Supply chain</td>
<td>A case-based model modification scheme that can generate modified formulation from the semantically specified requirements</td>
</tr>
<tr>
<td>Co-OPEATE</td>
<td>Azevedo et al. [1]</td>
<td>Supply chain</td>
<td>An integrated infrastructure designed on top of legacy transaction systems with XML being chosen for interoperation between heterogeneous systems</td>
</tr>
<tr>
<td>DISPOWER</td>
<td>Frey et al. [43], JWG University, Germany</td>
<td>Supply chain</td>
<td>A supply web is designed using agents to facilitate autonomous decision making for production planning and logistics</td>
</tr>
<tr>
<td>ISCM</td>
<td>Fox et al. [42], University of Toronto</td>
<td>Supply chain</td>
<td>Agent Building Shell (ABS); Coordination Language (COOL); functional agents</td>
</tr>
<tr>
<td>MaBE</td>
<td>Karageorgos et al. [65], UMIST, UK</td>
<td>Virtual enterprise; production planning</td>
<td>A holonic agent approach for manufacturing and logistics service planning; Nested Contract Net</td>
</tr>
<tr>
<td>Madefast</td>
<td>Cutkosky et al. [32], Stanford</td>
<td>Collaborative engineering</td>
<td>Using the Internet</td>
</tr>
<tr>
<td>MADEsmart</td>
<td>Jha et al. [63], Boeing</td>
<td>Collaborative engineering</td>
<td>Wrapper agents for legacy system encapsulation</td>
</tr>
<tr>
<td>MAGNET</td>
<td>Babanov et al. [2], U of Minnesota, USA</td>
<td>Supply chain</td>
<td>Genetic market architecture; contract negotiation with temporal and precedence constraints</td>
</tr>
<tr>
<td>MASCOT</td>
<td>Sadeh et al. [116], CMU</td>
<td>Supply chain</td>
<td>A reconfigurable and multi-level agent-based environment, blackboard architecture, mixed-initiative decision support</td>
</tr>
<tr>
<td>MASSYVE</td>
<td>Rabelo et al. [109], University of Santa Catatina, Brazil</td>
<td>Scheduling of virtual enterprise</td>
<td>An agile scheduling approach proposed for VE environment based on HOLOS [110]</td>
</tr>
<tr>
<td>MetaMorph II</td>
<td>Shen et al. [125], University of Calgary</td>
<td>Intelligent manufacturing, supply chain</td>
<td>Hybrid architecture; mediators as subsystem coordinators and interfaces to the main system</td>
</tr>
<tr>
<td>NIIP-SMART</td>
<td>Barry et al. [7], IBM Corporation, USA</td>
<td>Enterprise integration and enterprise collaboration</td>
<td>Standards-oriented configurable object model; product data exchange and business integration of MESs and EISs</td>
</tr>
<tr>
<td>SCADAS</td>
<td>Gupta et al. [51], Wichita State University</td>
<td>Supply chain</td>
<td>Using mobile agents to exchange operational information in a supply network; information privacy of companies is protected</td>
</tr>
<tr>
<td>VIRTEC</td>
<td>Bremer and Molina [12], DaimlerChrysler, AG</td>
<td>Virtual enterprise</td>
<td>Three components: virtual enterprise broker, virtual industry cluster, and virtual enterprise</td>
</tr>
<tr>
<td>Brugali et al. [16], Politecnico di Torino Choi et al. [24,25], Dong-A University, Korea Kuo [70], FJCU, Taiwan Lo Nigro et al. [76], University of Palermo and University of Basilicata, Italy Papaioannou and Edwards [98], Loughborough Swaminathan et al. [135], CMU Trappay et al. [137], Tsinghua University, Taiwan Wu and Kotak [151], NRC-IFCI, Canada Zhou [159], Drexel University</td>
<td>Supply chain planning</td>
<td>An APS system is added to the Supply Net Simulator for planning; APS nodes (agents, standing for plants) can cooperate to reach a supply net plan</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Order selection, scheduling and optimization</td>
<td>Order transaction and planning process are automated through mathematics and GA algorithms embedded in agents and negotiation among agents</td>
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<tr>
<td></td>
<td></td>
<td>Business process management</td>
<td>Document-driven, mobile, agent-based business process management; agents are derived from ADEPT concept; Aglet is used for implementation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enterprise Collaboration</td>
<td>Cooperative and competitive negotiation strategies in a distributed enterprise network; their pros, cons and possible mixed strategies</td>
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<tr>
<td></td>
<td></td>
<td>Virtual enterprise</td>
<td>Using mobile agents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supply chain</td>
<td>Supply chain library with structural elements (agents) and control elements for coordination</td>
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<tr>
<td></td>
<td></td>
<td>Supply chain virtual enterprise</td>
<td>A global logistics service tracking system (OLSTS) using mobile agents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Project management</td>
<td>Tooling project management framework making up of L-Agent, P-Agent and D-Agent and their interactions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supply chain</td>
<td>A coevolutionary approach for agent coordination</td>
</tr>
</tbody>
</table>
Table 3
Summary of projects on agent-based manufacturing process planning and scheduling

<table>
<thead>
<tr>
<th>Project</th>
<th>References/organization</th>
<th>Application domains</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABACUS</td>
<td>McEleney et al. [84], UCB</td>
<td>Manufacturing scheduling</td>
<td>Using functional agents; BDI approach for agent design</td>
</tr>
<tr>
<td>ADDYMS</td>
<td>Butler and Ohtsubo [21].</td>
<td>Manufacturing scheduling</td>
<td>Agents represent physical resources; dynamic local resource scheduling</td>
</tr>
<tr>
<td>AMC</td>
<td>Goldsmith and Interrante [48]. Sandia Lab</td>
<td>Manufacturing scheduling</td>
<td>Using physical agents: part agents and machine agents</td>
</tr>
<tr>
<td>CAMPS</td>
<td>Miyashita [88]</td>
<td>Manufacturing planning, scheduling</td>
<td>Repair-based methodology together with constraint-based mechanism</td>
</tr>
<tr>
<td>CORTES</td>
<td>Sadegh and Fox [115]; Sycara et al. [136], CMU</td>
<td>Manufacturing scheduling</td>
<td>Micro-opportunistic techniques for solving scheduling problems</td>
</tr>
<tr>
<td>CSIMAS</td>
<td>Wang et al. [147], Tsinghua, China</td>
<td>CAPP and scheduling integration</td>
<td>A MAS design methodology consisting of agent model, composition model, and cooperation model</td>
</tr>
<tr>
<td>DAS</td>
<td>Burke and Prosser [18], University of Strathclyde</td>
<td>Manufacturing scheduling</td>
<td>Hierarchical architecture with agents representing resources, resource groups, and a scheduling process</td>
</tr>
<tr>
<td>eXPlanTech</td>
<td>Riha et al. [112], CTU, Czech</td>
<td>Production planning</td>
<td>Agent-based production planning using the ProPlanT technology [106]</td>
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<tr>
<td>HOLOS</td>
<td>Rabelo [110], Federal University of Santa Catarina, Brazil</td>
<td>Manufacturing scheduling</td>
<td>An open, agile and (re)configurable dynamic scheduling system based on a generic agent architecture; five levels of integration</td>
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<tr>
<td>LMS</td>
<td>Fordyce and Sullivan [41], IBM</td>
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<td>Using functional agents; voting protocol for communication</td>
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<td>MAPP</td>
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<td>Process planning</td>
<td>Combination of sequential and blackboard architectures</td>
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<td>ProPlanT</td>
<td>Pechoucek et al. [106], CTU, Czech</td>
<td>Production planning and management</td>
<td>Production management agent with a tri-base acquaintance model; production planning is done by an agent using expert knowledge</td>
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<tr>
<td>Sensible Agents</td>
<td>Barber et al. [6], U of Texas at Austin</td>
<td>Manufacturing scheduling</td>
<td>Implemented as CORBA objects communicating through ILU object environment</td>
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<tr>
<td>Babayan and He [3], University of Illinois-Chicago</td>
<td>Scheduling</td>
<td>Game theoretic cooperation using the multiple players (job agents) transferable utility game; n-job 3-stage flexible flowshop scheduling problem</td>
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<tr>
<td>Choi and Park [26], KAIST</td>
<td>Shop floor scheduling of shipbuilding yard</td>
<td>An economical method for developing intelligent agent systems</td>
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<tr>
<td>Corsten and Gössinger [28], University of Kaiserslautern, Germany</td>
<td>Scheduling</td>
<td>Opportunistic coordination policies for agent cooperation</td>
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<tr>
<td>Cowling et al. [30], University of Bradford, UK</td>
<td>Scheduling of steel production system</td>
<td>Local scheduling model (Tabu search + heuristics) is used for scheduling in each agent; global (dynamic) scheduling is solved by agent negotiations</td>
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<tr>
<td>Goldberg et al. [47], CMU</td>
<td>Resource allocation</td>
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<tr>
<td>Hasegawa et al. [52], Toshiba</td>
<td>Manufacturing planning, scheduling</td>
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<tr>
<td>Imberti and Tolio [57], Politecnico di Milano, Italy</td>
<td>Integration of process planning and production planning scheduling</td>
<td>Manufacturing planner agent (a virtual agent in virtual manufacturing system); for order negotiation phases</td>
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<tr>
<td>Jeong and Leon [62], Texas A&amp;M University</td>
<td></td>
<td>Modified Lagrangian relaxation; CICA agents handling coupling constraints</td>
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<tr>
<td>Kornienko et al. [68], University of Stuttgart, Germany</td>
<td>Dynamic optimal planning</td>
<td>The system is adaptive to disturbances through negotiation of agent emergency behaviors; the optimal process plan is reached by using distributed ant colony optimization in agents</td>
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<tr>
<td>Kouss et al. [69], Lee et al. [71], Dongguk University, Korea; University of Penn. State, US</td>
<td>Manufacturing scheduling</td>
<td>Each agent represents a work center</td>
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<tr>
<td>Lim and Zhang [72], University of Exeter, UK</td>
<td>Dynamic scheduling</td>
<td>A dynamic economy-driven negotiation protocol for collaboration in DMP (Distributed Multiple Project) environment</td>
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<td>Liu and Sycara [74,75], CMU</td>
<td>Integration of process planning and scheduling</td>
<td>Functional agent-based integrated dynamic process planning and scheduling system</td>
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<td>McDonnell et al. [83], Pennsylvania State University, USA</td>
<td>Job shop constraint satisfaction and optimization</td>
<td>CP and CR (Constraint Partition and Coordinated Reaction) for constraint satisfaction; Anchor and Ascend for distributed constraint optimization</td>
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</tr>
<tr>
<td>Mönch et al. [89], Tech U of Ilmenau, Germany</td>
<td>Production process planning and control</td>
<td>Cascading Auction; real-time process planning and production control; considering secondary resources for the generation of a “complete” plan</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dynamic resource allocation</td>
<td>HMS-based approach using agents</td>
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Table 3 (continued)

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<tr>
<th>Project</th>
<th>References/organization</th>
<th>Application domains</th>
<th>Main features</th>
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<td>Murthy et al. [91], IBM T.J. Watson</td>
<td>Manufacturing scheduling</td>
<td>A-team architecture</td>
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<tr>
<td>Sousa and Ramos [131,132], ISEP/IPP, Portugal</td>
<td>Dynamic manufacturing scheduling</td>
<td>A scheduling holon with coordination approach that could handle the “Indecision problem” and manufacturing disruptions</td>
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<tr>
<td>Usher [140], University of Mississippi, USA</td>
<td>Resource allocation; integration of process planning and scheduling</td>
<td>Special negotiation strategies are proposed for agent to cooperate on real-time resource allocation with good performance</td>
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<td>Valencia and Rabadi [141], Old Dominion Univ., USA</td>
<td>Job shop scheduling</td>
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<td>Wang et al. [148], Shenyang Institute of Automation, China</td>
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<td>Wu and Xiao [150], Tongji University, China</td>
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<tr>
<td>Zhang et al. [158], University of Connecticut, USA</td>
<td>Maintenance scheduling</td>
<td>A mobile multi-agent framework; price-based coordinating approach (using Lagrangian Relaxation); a maintenance network</td>
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Table 4
Summary of projects on agent-based shop floor control

<table>
<thead>
<tr>
<th>Project</th>
<th>References/organization</th>
<th>Application domains</th>
<th>Main features</th>
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<tbody>
<tr>
<td>AARIA</td>
<td>Parunak et al. [103], ITI</td>
<td>Manufacturing scheduling and control</td>
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<td>AMACOIA</td>
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<td>Flexible assembly lines design</td>
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<td>I-Control</td>
<td>Brennan et al. [13]; Wang et al. [146], University of Calgary</td>
<td>Manufacturing system control</td>
<td>Partial Dynamic Control Hierarchy (PDCH); Using agents to model IEC-1499 Functional Blocks [56]</td>
</tr>
<tr>
<td>IFCF</td>
<td>Lin and Solberg [73], Purdue</td>
<td>Manufacturing scheduling and control</td>
<td>Resource agents represent physical resources; market-like control model</td>
</tr>
<tr>
<td>FABMAS</td>
<td>Mönch et al. [90], Tech University of Ilmenau, Germany</td>
<td>Control of semiconductor fab</td>
<td>Proposed an agent-based scheme and ontology for control of semiconductor fab; uses PROSA reference architecture [153]</td>
</tr>
<tr>
<td>KRASH</td>
<td>Lockemann and Nimis [77]</td>
<td>Production planning and control</td>
<td>A simulation and evaluation approach comparing distributed agent approach with centralized approaches</td>
</tr>
<tr>
<td>MASCADA</td>
<td>Bruckner et al. [15], Daimler-Benz AG; KULeuven</td>
<td>Manufacturing scheduling and control</td>
<td>Emergent behavior in manufacturing control; proactive disturbance handling; hot pluggable agents</td>
</tr>
<tr>
<td>MASCOT</td>
<td>Parunak [101], ITI</td>
<td>Manufacturing scheduling and control</td>
<td>A shared ontology and a base set of realistic modules</td>
</tr>
<tr>
<td>Reagere</td>
<td>Berry and Kumura [9], Penn State University</td>
<td>Manufacturing scheduling and control</td>
<td>Based on blackboard architecture</td>
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<tr>
<td>SFA</td>
<td>Parunak [102], ITI</td>
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<td>Bussmann and Schild [20], DaimlerChrysler, AG</td>
<td>Production system control</td>
<td>A flexible transportation system with associated agent-based control; auction-based negotiation protocol with different negotiation control procedures</td>
</tr>
<tr>
<td>YAMS</td>
<td>Parunak [100], ITI</td>
<td>Manufacturing scheduling and control</td>
<td>One of earliest applications in the domain</td>
</tr>
<tr>
<td></td>
<td>Baker [4], University of Cincinnati</td>
<td>Manufacturing scheduling and control</td>
<td>Market-driven contract Net; forward and backward scheduling</td>
</tr>
<tr>
<td></td>
<td>Bruccoleri et al. [14], University of Basilicata</td>
<td>Exception handling (machine breakdown)</td>
<td>Machine agents negotiate for production plan using heuristics and fuzzy logic technologies</td>
</tr>
<tr>
<td></td>
<td>Duffie and Piper [34], Wisconsin</td>
<td>Manufacturing scheduling and control</td>
<td>Agents represent physical resources, parts, and humans; part-oriented scheduling</td>
</tr>
</tbody>
</table>
A Holonic Manufacturing System (HMS) is “a holarchy which integrates the entire range of manufacturing activities from order booking through design, production and marketing to realize the agile manufacturing enterprise”. An HMS is therefore a manufacturing system where key elements, such as raw materials, machines, products, parts, and AGVs, have autonomous and cooperative properties [33]. In an HMS, each holon’s activities are determined through cooperation with other holons, as opposed to being determined by a centralized mechanism. Agent technology has been used to implement the HMS concepts. In this type of systems, intelligent agents called 'holons' have a physical part as well as a software part.

With the same concepts and similar system architectures, the HMS consortium partners have developed their own testbeds using their existing software and hardware environments. Most of the early research results on HMS were reported only internally in the HMS consortium. However, some results have been published, for materials handling [27], manufacturing planning and scheduling [52,10,131,132], and intelligent manufacturing control [13,146]. HMS is one of the most successful projects under the international Intelligent Manufacturing Systems (IMS) Research Program. Recently, it is a very active research area with a large number of publications including several related books [33,81].

Applications of HMS have been at the inter-enterprise level on holonic collaborative enterprises [139], and mostly at the enterprise and manufacturing system level, and at the MES (Manufacturing Execution System) level [33,81].

4. Key issues in implementing agent-based manufacturing systems

Key issues related to agent-based cooperative systems, such as representation, ontology management, agent structure, system architecture, communication, system dynam-ics, overall system control, conflict resolution, legacy systems integration and external interfaces, have been discussed in [123]. Most of these issues are also applicable in agent-based manufacturing systems. In this section, we discuss those key issues especially related to agent-based manufacturing according to our first-hand experience and an analysis of the research projects summarized in Section 3.

4.1. Agent encapsulation

Among the different approaches used for agent encapsulation in agent-based manufacturing systems, two approaches are distinct: the functional decomposition approach and the physical decomposition approach.

In the functional decomposition approach, agents are used to encapsulate functional modules such as order acquisition, process planning, scheduling, materials handling, transportation management, and product distribution. There is no explicit relationship between agents and physical entities. Examples of this type of approach are ISCM [42], CIIMPLEX [107], ABACUS [84], LMS [41], and in some recent projects [24,25,151,70].

In the physical decomposition approach, agents are used to represent entities in the physical world, such as operators, machines, tools, fixtures, products, parts, features, and operations. There exists an explicit relationship between an agent and a physical entity. Examples can be found in MetaMorph I & II [82,125], ADDYSM [21], AARIA [103,5], YAMS [100].

The functional decomposition approach tends to share many state variables across different functions. Separate agents must share many state variables, thus leading to problems of consistency and unintended interactions. The physical decomposition approach naturally defines distinct sets of state variables that can be managed efficiently by individual agents with limited interactions.
The functional decomposition approach is very useful in integrating existing systems (e.g., CAD tools, ERP/MRP systems) and resolving legacy systems integration problems. Even in an agent-based manufacturing system using primarily the physical decomposition approach, the functional decomposition approach may still be useful. The agents encapsulating some special functions may be used to provide such services at the system level, such as facilitators in PACT [31], broker agents in CIIMPLEX [107], mediators in MetaMorph I & II [82,125], system monitors in DIDE [121] and in IFCF [73]. Therefore, in some situations, it is not easy to categorize an agent-based system into solely the functional or physical categories, and some researchers use the word “hybrid” for those systems in which heterogeneous physical agents are coordinated by other system-level functional agents. In this sense, most agent-based systems emerged till today can be called as using hybrid approaches, in which both physical and functional agent encapsulations are applied. This is especially true for large applications beyond the shop floor control level, such as enterprise integration and enterprise collaboration. In large scale system applications, functions are much more complex and they are hardly to function at the same layer. Agents are generally required to wrap legacy systems for integration concerns. Central or local coordinating agents are unavoidable. Other functional agents are also coexisted for administration, information management, decision support, and optimization purposes.

4.2. Agent organization

Three approaches can be distinguished for agent organization in agent-based manufacturing systems: the Hierarchical approach, the Federation approach and the Autonomous Agent approach.

A typical manufacturing enterprise consists of a number of, often physically distributed, semi-autonomous units, each with a degree of control over local resources or with different information requirements. For such a real situation, a number of agent-based manufacturing systems still use the hierarchical architecture, though it may be criticized for its centralized appearance. Examples can be found in HMS [143,19], ADDYMS [21], DAS [18], and the Production Planning and Control Structure by Fischer [37].

The Federation approach has a number of variations: Facilitators, Brokers and Mediators. In the Facilitator approach, several related agents are combined into a group. Communication between agents takes place always through an interface called facilitator. Each facilitator is responsible for providing an intermediate between local agents and remote agents, usually by providing two main services: routing outgoing messages to the appropriate destinations; translating incoming messages for consumption by its agents. CIIMPLEX, PACT and other SHADE-based projects [85,108] used this approach.

Brokers are similar to facilitators with some additional functions such as monitoring and notification. The functional difference between a facilitator and a broker is that a facilitator is responsible only for a designated group of agents, whereas any agent may contact any broker in the same system for finding service agents to complete a special task. Broker agents can be found in CIIMPLEX [107].

The Mediator approach is another type of federation architecture. In addition to the functions of a facilitator and a broker, a mediator assumes the role of system coordinator by promoting cooperation among intelligent agents and learning from the agents’ behavior. A detailed description of the mediator concept and architecture can be found in [82]. Applications using mediators in intelligent manufacturing systems can be found in [82,125,94].

Federation architectures are able to coordinate multi-agent activities via facilitation as a means of reducing overheads, ensuring stability, and providing scalability. The federation approach promises to be a good foundation upon which to develop open, scalable multi-agent system architectures [46].

The Autonomous Agent approach is different. Although different definitions have been proposed for autonomous agents, we argue that an autonomous agent should have at least the following characteristics: (1) it is not controlled or managed by any other software agents or human beings; (2) it can communicate/interact directly with any other agents in the system and also with other external systems; (3) it has knowledge about other agents and its environment; (4) it has its own goals and an associated set of motivations. DIDE used this approach for developing agent-based engineering design systems [121]. AARIA also used the Autonomous Agent approach, but with fixed negotiation protocols [103].

According to our experience, the Autonomous Agent approach is well suited for developing distributed intelligent design systems where existing engineering tools are encapsulated as agents and connected to the system for providing special services, and the system consists of a small number of agents. This type of architecture is also very useful for developing autonomous multi-robot systems. In the mediator architecture, a static or dynamic hierarchy is imposed for every specific task, which provides computational simplicity and manageability. This type of architecture is quite suitable for developing distributed manufacturing systems which are complex, dynamic, and composed of a large number of resource agents. A combination of above mentioned approaches as a hybrid approach was proposed in MetaMorph II [125] for developing more flexible, modular, scalable and dynamic manufacturing systems.

4.3. Agent coordination and negotiation

Coordination is central to the successful operation of agent-based manufacturing systems which are very complex and whose stability is essential. Without coordination, a group of agents can quickly degenerate into a chaotic col-
lection of individuals. This situation is absolutely unacceptable in real manufacturing enterprises.

The easiest way of ensuring coherent behavior would be to provide the group with an agent that has a wider perspective of the system. Such an agent then becomes the central controller of the system. This central controller could gather information from the agents in the group, create plans, and assign tasks to individual agents in order to ensure coherence. In fact, traditional centralized manufacturing systems use this approach, with sub-controllers arranged hierarchically under the central controller. Originally, the controllers were human agents, but more recently many of their functions are carried out by programmable logic controllers (PLCs). The difficulty of reconfiguring such hierarchical control systems, as production demands change, is one of the reasons for industrial interests in multi-agent systems which have the potential for reconfiguration.

Using a single central controller for a large group of agents has an obvious problem. As the group size increases, it becomes very difficult for the central controller to be informed of all the agents’ beliefs and intentions. Also such a controller can become a severe communication bottleneck and would render the remaining components unusable if it fails. Agent technology provides a natural way of overcoming this problem.

Among the various coordination mechanisms described for agent-based systems, five are fundamental: mutual adjustment, direct supervision, coordination by standardization, mediated coordination, coordination by reactive behavior. A detailed description of these mechanisms can be found in [123].

Negotiation is used in most agent-based manufacturing systems for resource allocation. The protocols for negotiation include the voting mechanism [41], Contract Net [130] or its modified versions, such as the Extended Contract Net Protocol (ECNP) proposed by Fischer et al. [38], the Market-Driven Contract Net by Baker [4], the B-Contract-Net by Scalabrini [118], and the Levelled Commitment Contracting Protocol by Sandholm and Lesser [117]. Other examples can be found in [34,100,95,120,21,113,124,94]. A bidding mechanism can be part-oriented [34,95,73], resource-oriented [21,4,124], or bi-directional [113].

Although the Contract Net and its variants are usually used as negotiation protocols in most agent-based scheduling systems, market-based approaches are becoming more and more popular. Market-based or like protocols use the so-called bargaining process or auction process, which is also simple and easy to use. Market-based or like approaches have been used in a number of agent-based scheduling systems (e.g., [4,73]).

Some researchers have also realized the game-like nature of independent scheduling decisions, and try to use game theory to make their agents smarter [50].

Very recently a new adaptive negotiation approach has been proposed by our group to address complex negotiation situations [145].

4.4. System dynamics

Real world manufacturing environments are highly dynamic because of frequently changing situations: bank rates change overnight, political situations change, materials do not arrive on time, power supplies breakdown, production facilities fail, workers are absent, new orders arrive and existing orders are changed or canceled. Deterministic mechanisms using a centralized control mechanism cannot handle the system dynamics of a complex system. Surana et al. [134] emphasized that the most remarkable phenomenon exhibited by complex systems is the emergence of highly structured collective behavior over time from the interaction of simple subsystems without any centralized control. They believed that a complex system such as supply chain networks should be treated as a “Complex Adaptive System (CAS)” and tackled by the CAS simulation and theory. Although agents are not explicitly used in this research and other similar approaches (e.g., [104]), the agent concept is perfectly matched with their CAS features and forms a feasible implementation infrastructure for CAS simulation and realization.

We use dynamic scheduling here to indicate that a real-time manufacturing scheduling system can update its schedule to adapt to changing situations such as new order insertion, machine failures, and job tardiness. ADDYMS developed a dynamic scheduling mechanism for local resource allocation at the local work cell level [21]. In MetaMorph II, several mechanisms were developed for dynamic scheduling and rescheduling by combining a bidding mechanism based on the Contract Net protocol with a mediation mechanism based on the Mediator architecture [124]. Sousa and Ramos [131] proposed a dynamic scheduling architecture using holons.

According to our experience, agent-based approaches are particularly suitable for dynamic manufacturing scheduling, but may not be the best solution for advance scheduling problems. Rehak et al. [111] also indicated that agent-based approaches may not be suitable for high-volume production environments.

4.5. Learning

For most industrial applications, it is extremely difficult or even impossible to correctly determine the behavior and concrete activities of an agent-based manufacturing system “a priori”, that is, at the time of its design and prior to its use. In fact, most changes and disturbances in manufacturing environments are not predictable in advance. This would require, for instance, that it is known a priori which environmental requirements will emerge in the future, which agents will be available at the time of emergence, and how the available agents will have to interact in response to these requirements. Such problems resulting from the complexity of agent-based systems can be avoided or at least reduced by endowing the agents with the ability to learn, that is, with the ability to improve the future
4.6. Optimization

Optimization is the major research objective in manufacturing technology and management. Agent-based approaches primarily emphasize on the agility and reconfigurability of manufacturing systems. However, optimization is also one of the most important objectives in designing and implementing agent-based manufacturing systems. Different from the mathematical approaches targeting at a global optimization through mathematical formulation of industrial problems which are usually impossible for complex manufacturing systems, agent-based approaches attempt to achieve optimization through efficient coordination mechanisms. Agent-based cooperative scheduling through negotiation among agents is a typical way to achieve optimization at various levels: supply chain, enterprise, shop floor, and individual machine level. Most agent-based systems take this kind of approach (e.g., [125,43,158]). However, there are also some other systems having an Optimization Agent to take care the coordination role (e.g., AGENT-OPT by Chan and Lee [23]), which is similar to the approach used in traditional centralized manufacturing systems.

4.7. Security and privacy

A major concern of implementing Internet-enabled agent-based manufacturing systems is the assurance that proprietary information about the intellectual property owned by an organization or information about the company operations is available only to authorized individuals. Internet-based manufacturing involves sharing intellectual property in the form of detailed engineering and manufacturing information as well as competitive information in the form of order and cost details. For general acceptance of the agent-based manufacturing approach, the secrecy of the proprietary or competitive information must be maintained.

In addition to maintaining secrecy, Internet-enabled agent-based manufacturing systems must also accommodate the privacy of the individuals and organizations involved in collaborative manufacturing activities. Gathering and processing information about the activities of individuals or groups while managing or operating processes or machinery via computer networks can provide a great deal of details concerning the ways in which the individuals interact as well as process-related information. In a highly competitive manufacturing environment, we must ensure that information about the operations of or the information provided by individuals or organizations is only shared in a fashion dictated by those involved.

Security and privacy are critical issues in implementing Internet-enabled agent-based manufacturing systems. The major concerns include:

- Socket communication is actually used for inter-agent message exchange. Although secure sockets can be used to enhance the communication security, an implementation in a real shop floor may have some difficulties because of firewalls;
- Although most systems are implemented on the enterprise’s intranet behind a firewall, communication across different intranets or the Internet may be needed in case of outsourcing;
- Mobile agents with product data traveling across the Internet may cause more concerns.

However, the security problem resulting from the open architecture of agent-based systems, particularly when using the Internet and the mobile agent technology, has been recognized by both manufacturing enterprises and the researchers in this area. This is not unique to agent-based systems and may be mitigated through further researches.

4.8. Tools and standards

Wide use of agent technology in industry depends on the availability of development tools and platforms. Such tools and platforms, in turn, presume the existence of standards that reflect the agreement of developers on which basic functionality should be and how it should be presented. Some efforts have been devoted to providing standards for agent-based systems, but no standards can be found for developing agent-based manufacturing systems.

The Foundation for Intelligent Physical Agents (FIPA) (http://www.fipa.org/), founded in 1996, is an international standardization organization promoting the development and specification of agent technologies. The main goal for FIPA specifications is to specify how different kinds of agent platforms can interoperate. Since December 2002, the first set of FIPA specifications have been available (http://www.fipa.org/specifications/), and a number of FIPA compliant agent platforms have been developed (http://www.fipa.org/resources/livesystems.html). Among them, three well-known agent platforms are: JADE (http://jade.tilab.com/), FIPA-OS (http://fipa-os.sourceforge.net/) and ZEUS (http://more.btexact.com/projects/agents/zeus/). In addition to a dozen of agent platforms recognized by FIPA, several dozens of other platforms have also been developed and claimed to be FIPA compliant and even more commercial or academic agent platforms have been reported and can be found over the Internet, with different mixes of mobility, adaptability, intelligence, ACL and multi-language support. Comparisons of agent platforms from various facets can be found in [142,40,92]. Since June 2005, FIPA joined IEEE Computer Society as its eleventh standards committee to pro-
mote agent-based technology and the interoperability of its standards with other technologies.

Another significant effort on related specifications is the National Industrial Information Infrastructure Protocols (NIIIP) (http://www.niiip.org/). It is a consortium of US companies formed to develop open industry software protocols that will make it possible for manufacturers and their suppliers to effectively inter-operate as if they were part of the same enterprise. Although it does not focus on agent specifications, some specifications and protocols have been widely used to develop agent-based manufacturing systems, particularly for virtual enterprises and supply chain management.

Even though so many agent platforms have been available, most projects or research work reviewed in our previous survey [122] use traditional programming languages, such as C++, Java, Lisp, SmallTalk, Prolog, and Objective C to develop agent-based manufacturing systems. Other recently developed agent systems use Jini network technology (http://www.sun.com/jini/). Most recently developed agent-based manufacturing systems are Java-based systems. Some of them utilize existing agent development tools for fast prototyping and standards compliance reasons. Many researchers are still developing proprietary agent frameworks (particularly for industrial applications) even though hundreds of open source or commercial agent development tools have been available, since most industrial companies cannot accept GPL or LGPL licenses of open source tools and commercial tools are not cost effective enough for industrial application developments yet.

Some agent systems have been developed using distributed object technologies such as Microsoft’s COM/ DCOM/COM+, OMG CORBA (http://www.omg.org/ corba/). In fact, most Java-based agent platforms have been developed on Java RMI. Some other early developed agent communication languages are still being used, e.g., KQML [36] together with KIF [45] as a common content format, and STEP [11] for providing semantics of messages in manufacturing applications.

5. Concluding remarks

Software agents and their applications in intelligent manufacturing have been studied for about two decades. However, industrial applications are still rare compared with other technologies such as Distributed Objects and Web-based technologies. This might be primarily due to the fact that the majority of research and development work in this area has been done within the academic community. This situation may change since FIPA joined IEEE Computer Society as one of its standards committee, which means that the FIPA specifications will be converted to IEEE standards.

Since 1998 when our previous survey [122] was completed, a large number of related projects have been reported through various conferences and journal publications. During this updated literature review, we found several hundreds of related publications, reviewed about 100 papers (related to about 70 different projects). However, many recent projects are very similar to those completed before 1998. No significant advancements in this area can be seen during the past 7 years. Some difficult problems remain unsolved, e.g., full integration of manufacturing process planning, scheduling, and control, particularly integration with real time information from data collection systems.

The agent technology is still considered to be “nice-to-have” by industrial people. It seems that there is still a long way to go before it is considered to be “must-have”. We believe that the agent technology must be integrated with other technologies such as Web-based technologies (including Web Services and Semantic Web) and Grid computing for its wide and successful applications in industry in a near future.

Many researchers (particularly Ph.D. students) working on agent-based manufacturing are still focusing on the fundamental research to enhance the rationality or intelligence of software agents and develop more efficient and effective coordination and negotiation mechanisms. While this kind of research is important and still needed, we believe that the future R&D work should focus on the integration of agent-based planning and scheduling systems with existing systems used in manufacturing enterprises. The most important integration is with real time data collection systems, including SCADA (supervisory control and data acquisition) systems and RFID (radio frequency identification) systems. Another important integration is with existing ERP and MRP systems. Note that a certification is required for integrating or interfacing with some commercial ERP/ERP systems. Only when such integrations are achieved and validated in industrial settings, will the agent technology be widely applied in manufacturing industry.

References


[34] N.A. Dufle, R.S. Piper, Non-hierarchical control of manufacturing systems, JMS 5 (2) (1986) 137–139.


