INT. J. PROD. RES., 2000, VOL. 38, NO. 17, 4129–4148

Autonomy and viability—measures for agent-based manufacturing systems

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An Agent-Based Manufacturing System (ABMS), represented as a model of future manufacturing systems, is introduced in this article. In an ABMS, computerized agents are autonomous and working collaboratively through the regulation of structured dialogues. The autonomy functions of an agent are demonstrated by four internal functions: *internal resource management, a reflexivity mechanism, a goal adjustment mechanism*, and *collaboration management*. The four functions assist an agent in interacting with other agents and with the environment and to adjust itself to the situation in the dynamic environment. Agents are similar to living systems. Based on the concept of living systems, autonomy and viability at the agent level are proposed and defined as new measures for manufacturing systems. A theory of coexistence and parasitism of ABMS is developed to identify the coexistent and parasitic characteristics of ABMS. Applications of the theory to real cases are also illustrated. Finally, a road map for the future research of distributed, collaborative manufacturing organizations is shown, based on the ABMS model developed.

1. Introduction

Computer and communication (C&C) technologies have revolutionized the behaviours of manufacturing systems (Tharumarajah *et al.* 1996, Rogers and Bottaci 1997, Huang and Nof 1999b). Traditionally, decision-making and operations in manufacturing systems are centralized, routine, and geographically restricted. Nowadays, the behaviours of decision-making and operations are distributed, autonomous, and global-oriented (Browne *et al.* 1995, Rzevski 1997). However, a model is still lacking to guide the development of distributed and collaborative manufacturing systems. Agent-Based Manufacturing System (ABMS) is an emerging model and design approach that tries to describe the behaviours of those distributed operation and decision-making units in manufacturing systems. Even though Huang (1995) has initialized the development of ABMS, it still lacks a theory and measures to formulate ABMS. This research focuses on bridging the agent theory to manufacturing systems, so a new manufacturing system paradigm can be developed. In order to achieve the goal, the following research problems are defined:

(1) *How can an agent be specified from the perspective of manufacturing systems?* Many research articles have proposed the concept of agents for various systems (e.g. production systems, information systems, etc.). However, the internal, autonomous functions of an agent, which are as important as the framework of an agent (Gasser 1994), are seldom defined. In the

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International Journal of Production Research ISSN 0020–7543 print/ISSN 1366–588X online
http://www.tandf.co.uk/journals

manufacturing system domain, how to specify the internal functions of an agent becomes the first issue for studying agent-based manufacturing systems, because the internal functions affect the interactive and collaborative behaviour (Wegner 1997) of agents.

(2) *How can an ABMS be specified?*
An ABMS is classified as a new paradigm of manufacturing systems. However, the definition of agent-based systems is still unclear. How to describe an ABMS based on the given definition of agents and how to describe the behaviour of the collaborative agents are research questions.

(3) *How can autonomy and viability be defined for an agent and an ABMS?*
Traditional manufacturing systems are usually hierarchical and measured by productivity, flexibility and integrity. These three measures were developed for systems that are passive, with few interactions and have little collaboration with other systems. These three traditional measures cannot fulfil the needs of ABMS, because agents in ABMS are individual, communicative, autonomous, and are always trying to collaborate with other agents and look for collaborators; agents are similar to living systems (Steels 1995). Two measures, autonomy and viability, are commonly applied to measure how well a living system is suited to its environment. Yet their definition and application to ABMS, which is based on a similar concept of living systems, is unknown. It is necessary to build a measure system based on autonomy and viability to illustrate the behaviours of ABMS.

This research is performed to resolve the above problems. The remainder of the article is organized as follows. In section 2, the associated literature on agents, ABMS, autonomy, and viability is reviewed. In section 3, the definitions of an agent and a proposed structure of ABMS are illustrated. In section 4, the definition of autonomy and viability for agent level and system level are specified. Based on the viability defined, a theory of coexistence and parasitism for ABMS is defined in section 5. Practical examples based on the theory are also illustrated. Finally, concluding remarks and future research are presented in section 6.

2. Literature review

In this research, the literature is reviewed from four perspectives: (1) definition of an agent, (2) classification of an agent, (3) autonomy, and (4) viability. Based on the literature review, a structure of agent-based manufacturing systems is constructed, upon which autonomy, viability, and their associated theories are developed.

2.1. *Definitions of an agent*

An agent is defined by its characteristics, and researchers propose various characteristics for agents. Unfortunately, sometimes a definition of a characteristic proposed by one researcher might conflict with that proposed by another. In order to find common characteristics and develop a more acceptable definition, a comparison is made in table 1, where the four key characteristics in eight articles are:

(1) autonomous;
(2) communicative;
(3) goal oriented;
(4) reactive.

6. Conclusions and future research

6.1. *Conclusions*

Future manufacturing systems are characterized by *autonomy*, *distribution*, *communication*, and *collaboration*. Those characteristics are enabled by computer and communication (C&C) technologies. However, a systematic method is not yet available to integrate those characteristics into the analysis and design of manufacturing systems. Meanwhile, the literature review in this research indicates that C&C technologies have enabled a system paradigm shift from Turing machines to interactive machines (Wegner 1997). Under the paradigm shift, this research has been developed to resolve the following research problems.

(1) *How can an agent be specified from the perspective of manufacturing systems?*
This research identifies four unique characteristics (autonomy, goal-orientation, being able to communicate and reflexivity) for agents of manufacturing. Those four characteristics support the development of the internal functions of an agent described in section 3.

(2) *How can an ABMS be specified?*
ABMS is one of the models of future manufacturing systems. Future manufacturing systems are identified by the characteristics of autonomy, distribution, integration, cooperation and collaboration. In section 3, a framework of agent-based manufacturing systems (ABMS) is proposed.

(3) *How can autonomy and viability be defined for an agent and an ABMS?*
The paradigm shift also results in a reassessment of measurement systems for ABMS. Since an agent is similar to a living system, two measures, autonomy and viability, which are commonly applied in living systems, should be also defined for ABMS. In section 4, definitions of autonomy and viability are addressed. Based on the concepts of autonomy and viability, agents in an ABMS are further classified into *coexistent* agents and *parasitic* agents. The classification results in the development of three theorems. The three theorems are found applicable to explain real-world situations and provide possible solutions.

6.2. *Discussion and future research*

A common keyword in today's research into manufacturing systems—such as supply chain management, manufacturing logistics, enterprise resource planning, and global manufacturing—is 'distribution'. C&C technologies have made decision-making possible for distributed enterprises. Even though the technologies enable the communication and computation in enterprises, methodologies for design and control enterprises that are highly autonomous are not yet available. Traditional industrial engineering methodologies that are rooted in the concept of centralization and limited computing resource are challenged by the facts that enterprises are distributed and communicate with each other with the support of powerful and intelligent computers, connected by fast communication facilities.

This research pinpoints a theoretical structure for distributed and autonomous manufacturing systems in the future. However, the evaluation of such a distributed, autonomous organization still needs future investigation. The results may be extended into two directions (figure 10): *distributed enterprises* (in control/execution level) and *virtual enterprises* (in planning/simulation level). Distributed enterprises are commonly studied. However, the autonomy of distributed enterprises is not