Self-organization in a distributed manufacturing system based on constraint logic programming

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Abstract

The paper addresses the problem of self-organization of manufacturing systems. The objective is to overcome the rigidity of conventional hierarchical structures and to introduce structures that are able to adapt to a dynamic environment. The presented approach is based on the concept of Complex Adaptive Manufacturing Systems. It is characterized by a decomposition of manufacturing objectives and allocation of tasks to work systems as autonomous building blocks in a dynamic environment. The allocation is based on a market mechanism that enables self-organization and optimization of a manufacturing system by evaluation and selection among competing work systems. The approach is implemented in the Constraint Logic Programming environment Eclipse and validated in a simulation experiment.

Keywords: Optimization, Multi-agent structure, Work system

1 BACKGROUND AND MOTIVATION

Rising complexity of products, production structures and processing procedures [1] on one side and turbulent market excitations resulting in growing product variety, individualization and shortening time frames on the other are setting new frontiers to the manufacturing business. Despite of research efforts and investments in the context of Computer Integrated Manufacturing the existing manufacturing systems are still predominantly based on the obsolete Taylorian philosophy. Therefore they cannot adequately conform to these requirements because of their structural rigidity, deterministic approach to decision making in a stochastic environment, hierarchical allocation of competencies, and insufficient communication and exploitation of expertise.

In order to face new challenges in manufacturing a shift of the existent manufacturing paradigm from deterministic into a new manufacturing prospect considering natural understanding and concern is needed. Several influencing concepts in this direction have emerged in the last decade: Fractal Factory [2], Bionic Manufacturing Systems [3], Holonic Manufacturing Systems [4], and Distributed Manufacturing Systems (DMS) [5]. These concepts influenced research for more effective mastering of complex and dynamic behavior of the system and its environment, especially the Holonic and Distributed Manufacturing Systems concepts [6,7,8]. In the paper the results of further developments of the Distributed Manufacturing Systems concept are presented.

2 APPROACH

About two centuries ago Adam Smith in his work The wealth of nations tried to explain the mechanism which was driving the society [9]. He argued that the rule of allowing people to do what was best for them was introducing a sort of a self-organizing mechanism. This simple rule was the foundation of the market system. The market system is a self-organizing social system controlled, regulated, and directed by the market alone; order in the production and distribution of goods is entrusted to this self-regulating mechanism – the 'invisible hand' as noted by Smith.

Nowadays the global economy is still propelled by this idea. The market system is strongly influencing the behavior of a manufacturing company as a whole but due to its closed structure it is affecting only those elements, which are in a direct contact with the market. Other structural elements are subordinated into a hierarchy and are little if not at all influenced by the market system.

Here it is assumed that a break up of the closed hierarchical structure would let the market system to influence every element of the system's structure and would induce the self-organizing principle based on two factors described by Smith that make the market system work: self-interest and competition.

Various authors have adopted the micro-economic model of self-organization on the production planning and control scale. Some promising results have been obtained [7, 8, 10]. The common observations can be summarized: (1) the architecture is the essential issue, (2) the role of a human subject is dominant, (3) the information and communication technologies are the enabling technologies, and (4) the transition from highly data-driven to particular information, knowledge and learning driven organization is needed.

Therefore new features of future manufacturing systems have to be developed. The most expected ones are: (1) an open multi-level architecture, (2) advanced communication capabilities, (3) decentralized decision making, (4) self-organization ability, and (5) redefined work systems in terms of autonomy, evolutionary adaptivity, reconfigurability, co-operativeness, interactivity, task orientation within competence, ability of communication, coordination and cooperation, and learning capability.

This research is focused on the problem of how a manufacturing system can self-organize for a given objective (for instance the realization of a product) and how the system can adapt its structure in case of external and/or internal disturbances (e.g. machine break down).

2.1 Agent Based Approach

Peklenik [11] interprets the concept of DMS in terms of a Complex Adaptive Manufacturing System (CAMS), which is structured as a network of many agents acting in parallel, in series, or in both ways. Each agent is acting with other agents in an environment, generated by a web of interactions.

Within the concept the basic building blocks are defined in terms of elementary work systems (EWS) with autonomous behavior and having the competence and capabilities to perform a particular manufacturing operation. An EWS consists of hardware elements necessary to implement a work process, work process identification for process control and optimization, and a human operator as an autonomous subject for making decisions and synthesis [11].

The presented approach of self-organization is based on the CAMS architecture. The self-organization is implemented in the multi-agent technology and controlled by the market mechanism. A virtual work system (VWS) is introduced in order to delegate the EWS in a distributed environment. The VWS is an agent and it represents the EWS as its counterpart in the information space. It is a software entity having four basic functional elements: perceptor, evaluator, effector, and inference mechanism [10]. The role of the perceptor is: (1) to observe a state of the environment in order to recognize relevant information, (2) to form inputs from this information, and (3) to trigger the evaluation process. The inference mechanism controls the evaluation by reasoning. The reasoning process is based on embedded data and knowledge with the reference to a set of goals. Output is launched into the environment by the effector and thus affects the state of the environment. Autonomy and viability are the key attributes of a VWS.

There exist several similar approaches, which implement the agent technology as well, e.g. [7, 8, 12, 14]. In these approaches agents are software entities that model the factory's functions and/or physical entities (e.g. orders, parts, resources). However they do not represent a manufacturing structure and thus the reduction of complexity is limited. In our approach the complexity can be managed more efficiently as the building blocks are systems - EWSs.

2.2 Constraint Logic Programming

Constraint Logic Programming (CLP) is a natural merger of two declarative computational paradigms: constraint solving and logic programming. The combination involving the incorporation of constraints and constraints solving methods in a logic based language helps to make CLP programs both expressive and flexible, and in some cases, more efficient than other kinds of programs. The collection of dynamically generated constraints in every state is tested as a whole for satisfiability in order to control execution [15]. A crucial property of any CLP implementation is that its constraint handling algorithms are incremental. Constraints allow the declarative interpretation of basic relationships, and rules combine these for complex relationships. So a transparent representation of the problem is obtained. The embedded consistency techniques exploit the constraints to reduce the domains of variables as soon as new information is available. New information triggers the related constraints, which results in reduced domains of the concerned variables. Such execution can be viewed as data-driven. Constraints are active in the sense that they do not wait to be explicitly called, but they activate automatically when relevant information appears [16].

The basic arguments for the use of CLP in the concept implementation are as follows. There are complex strategies which are usually formulated as rules, there is a combinatorial aspect to the problem, a combination of symbolic and numeric computation is involved, flexible "what-if" type analysis is required, dynamic state of the environment can be efficiently expressed and dynamically processed in terms of constraints.

3 SELF-ORGANIZATION IN DMS

In a traditional manufacturing system allocation of manufacturing tasks to resources is a typical scheduling problem. The scheduling is defined as planning of *n* tasks over *m* resources to be processed at or during a particular time. The issue of planning and control in DMS is not limited only to classical scheduling but first of all it must focus on the appropriate structuring of the system. Although tasks and time frames are defined potential resources for the task execution are not known in advance. So the point is to build dynamic structures for each task based on a self-organization principle.

A DMS is constituted of a set of heterogeneous and redundant EWSs, which are interconnected via corresponding VWS agents into a network. The agents operate and communicate over the network and coordinate their actions to accomplish complex tasks by exploiting their competence. For realization of a complex task, i.e. a manufacturing order, particular work systems join a cluster, which represents a temporal manufacturing structure. A cluster is built up upon coordination of two parties, one representing demand and the other supply. Agents representing demand are mediators that control a process of making coordinated solution for a given task. Agents representing supply are VWSs. Thus, the structuring of a DMS is goal oriented and is driven by self-interest and competition. Self-interest is a common property of agents and is related to individual objectives. Competition is a consequence of redundancy in the system.

The coordination process implies task decomposition as a recursive task structuring process. The dynamic structuring process consists of bidding-negotiation-contracting phases and is performed via the extended contract net protocol adopted from [17].

The process builds up task-oriented manufacturing structures. For example in a parts fabrication domain the fabrication of a part is performed in a sequence of tasks that are executed by corresponding work systems. In principle in process planning there are several alternative sequences carried out for each part. The objective is to structure the manufacturing system in such a way that the fabrication is accomplished to a selected scenario, e.g. with the best-cost performance in a given time frame under actual circumstances. The proposed mechanism of building task-oriented structures is shown in Figure 1 and carried out in the following procedure.

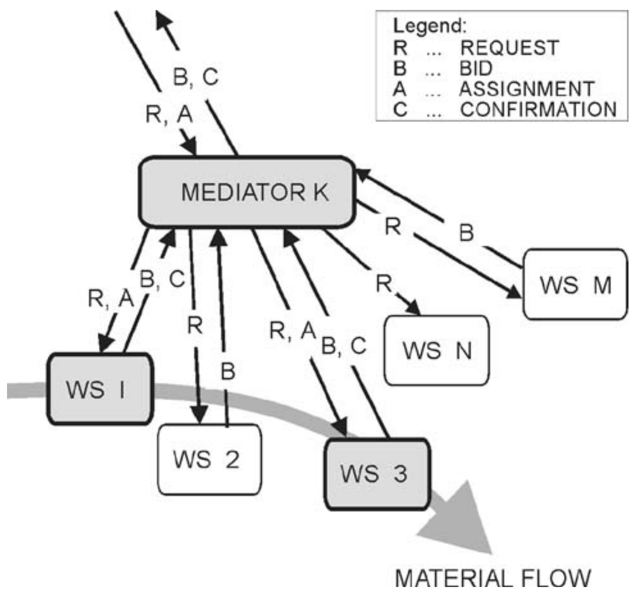

Figure 1: Self-organization process