The Fabricare system: a multi-agent-based scheduling prototype

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Abstract. Several trends in society in general, and manufacturing in particular, have changed the way business was made in the last decades of the 20th century, setting new requirements for companies and individuals. The research question being addressed in this paper is concerned with the ability to build computer-supported manufacturing systems able to cope with current and future requirements. For this matter, a hypothesis based on the holonic and multi-agent paradigms is proposed. The paper describes a holonic architecture for manufacturing enterprises and a prototype system (named Fabricare) for manufacturing orders scheduling based on that architecture.

A negotiation mechanism called ‘contract net with constraint propagation protocol’ was developed for regulating the interaction between holons in the system. This protocol also implements a negotiation-driven scheduling procedure.

1. Introduction

Society has experienced evolving mutations since the dawn of ages, especially in the last half of the 20th century. In recent years several trends were observed in manufacturing and society, namely: market globalization; increasing product/services customization; increasing technology

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complexity; increasing number of competitors; decreasing product life cycles; and increasing quality requisites (Kusiak 1990, Solberg and Kashyap 1993, NGM 1997). Stability, certainty and predictability are giving place to change, uncertainty and unpredictability (Kidd 1994). In addition, a shift towards flexible manufacturing and customized products is evident (Atkinson and Court 1998).

From a technological point of view, it was observed that current manufacturing systems (e.g. computer-integrated manufacturing architectures) pose several drawbacks, namely excessive rigidity and centralization; high implementation costs; and inflexibility (Höpf 1994, Ueda 1994, Bongaerts *et al.* 1995, Parunak 1996, Tharumarajah *et al.* 1996, Gou and Luh 1997, Bussmann 1998, Kadar *et al.* 1998, Shen and Norrie 1999). Furthermore, it is expected that in the future manufacturing will be characterized by: globally distributed resources; small quantities and high variety of products; providing individual solutions tailored to each customer's specific needs; concurrent execution of all the activities in the manufacturing process (NGM 1997, CVM 1999).

In order to deal with the identified problems with current manufacturing systems and prepare them for the expected future scenarios, the new generation of manufacturing systems must possess such attributes as decentralization, distribution, autonomy, adaptability and incomplete information handling (Sousa *et al.* 2000b, c).

New approaches have been proposed, providing systems that are more adequate in a current and future social-economic context. Multi-agent systems (MAS) (Parunak 1998) and holonic manufacturing systems (HMS) (Valckenaers *et al.* 1994a, b, 1997) appear as promising approaches to this point.

This paper presents a system, named 'Fabricare', based on holonic principles, for dynamic scheduling of manufacturing orders. The system tries to achieve the following user's needs:

- *High flexibility* – cope with change in system's structure and behaviours (e.g. cardinality of resources, resource's functionality);
- *High adaptability* – cope with change in system's dynamics (e.g. machine breakdown) and in markets;

- *High availability* – reduce downtime (hence cost) and single point of failure.

These user needs were translated into objectives, which are seen in this work from a software point of view. That is, for instance, availability relates to the software system availability and not to machine or tool availability.

2. System architecture

This work tries to present an integrated view of a manufacturing system, based on the distributed manufacturing system paradigm, able to accomplish the requirements for the post-20th century society (Sousa *et al.* 2000a). In order to overcome these challenges, a solution based on holonic manufacturing systems has been proposed using multi-agent systems and extended logic-programming. Although overlapping, the two concepts, MAS and HMS, complement each other, especially by using MAS as an implementation tool for HMS (Bongaerts 1998, Bussmann 1998, Kirsch *et al.* 1998, Sousa *et al.* 2000c, Ulieru *et al.* 2000). To the scope of this work, a holon is understood as a logical design entity in the system architecture, and is implemented as an agent using extended logic programming. Although not necessarily a matter of consensus, both words (holon and agent) can be used as synonyms in this paper.

In this solution, Fabricare, which is the Latin word for 'to manufacture', the main entities in the manufacturing process are modelled as holons, each one contributing with a small parcel of the overall system's functionality.

The Fabricare project uses a holonic architecture (figure 1) where several key functions of the manufacturing process are identified and modelled as holarchies (Sousa and Ramos 1998, 1999, Sousa 2000). These holarchies are composed of 'basic' holons such as product, task and resource, each one representing a core entity in the manufacturing system.

The core holons are grouped together in holarchies representing the major function of the manufacturing system. The design holon (DH) aggregates product holons (PH), customer holons (CH) and supplier holons (SuH)

Figure 1. The architecture of the Fabricare project.

for the design activity. The process planning holon (PPH) aggregates resource holons (RH) and product holons (PH). The production planning holon (ProdPH) aggregates resource holons and sales holons (SaH) to execute material requirements planning and capacity planning. The scheduling-holon (SH) aggregates resource holons and task holons (TH) to dynamically schedule manufacturing orders. Additionally, there is the directory service (DS) that acts a repository for the system providing information about running holons.

3. Holon interaction

In order to regulate the interaction between Fabricare's holons, a protocol is used, aiming to achieve cooperation. The participants in this protocol are task holons and resource holons. Task holons represent a manufacturing order to be executed by the shopfloor, while resource holons represent the physical machinery on the shopfloor.

For the scheduling of task's sub-operations, the task holon will negotiate with resource holons, using an extension of the contract net protocol (Smith 1980, Davis and Smith 1983) with a cooperation phase between service providers (i.e. resource holons). The resource holons will use constraint propagation in order to guarantee the relationships among different operations that aim at the same task. This new protocol is called 'contract net with constraint propagation protocol' (CNCPP) (Sousa and Ramos 1997, 1998, 1999, Sousa *et al.* 1999, Sousa 2000) (figure 2).

After receiving a request, each resource holon will be 'forward-influenced' by its predecessors and will forward-influence its successors. Likewise, each resource holon will be backward-influenced before making its bid, and will backward-influence its predecessors (Sousa and Ramos

1999, Sousa 2000). The 'forward' and backward-influence operations consist in adjusting the beginning and the end of each resource's agenda of free time intervals with the agenda of predecessor/successor resources (i.e. delete from the list of free time intervals, those intervals where it is impossible to schedule the operation because the part is still being processed by other resources (Ramos *et al.* 1995)). The set of resources participating in a specific negotiation is built at the beginning of that negotiation by the task holon. If new resource holons are added to the system they will not be considered for running negotiations but will enter future ones.

Since multiple tasks can be negotiated at the same time, conflicts may arise if some resources are used in the same time interval for different tasks. In these scenarios, resource holons have an indecision problem (Sousa and Ramos 1998) since they cannot guarantee the delivery of both tasks. In order to overcome this problem, a solution is proposed which involves a pre-negotiation step in the protocol. Before beginning negotiation, each task holon will ask for authorization from the scheduling holon, which maintains a list of negotiating resources and respective time windows. Only in the case of non-overlapping a 'green light' will be given to the negotiation.

The system is prepared for overlapping functionality on the resource holons, i.e. different resource holons can perform the same operation (e.g. drill). A task holon will receive the production plan for a product with indication of the necessary operations, and will request them to every resource holon able to perform each operation. This causes a combinatorial explosion in the number of exchanged messages between agents (with an $O(r^n)$ complexity, where r is the number of resources and n the number of operations). To decrease the number of messages a modification was made in the protocol, in

Figure 2. Contract net with constraint propagation protocol (CNCPP).

which combinations from predecessor resources are clustered before sending them to successor resources (Sousa 2000). This change has made the complexity of the problem $O(n)$ in which respects the number of exchanged messages. However, the problem of a combinatorial explosion in the search space still exists (possible solutions for this problem are being addressed).

The scheduling procedure is adapted from a centralized method described in Ramos *et al.* (1995) and Almeida (1995), based on agendas, behaviours and due dates. Behaviours are static resource allocation mappings, which are pre-generated for each production plan. The calculations for time intervals are performed by the resource holons when executing the contract net with constraint propagation protocol. When compared to the original scheduling procedure from Ramos *et al.* (1995), Fabricare's approach has the ability to use alternative resources for each operation as well as using the same resource for more than one operation in the same production plan.

The same protocol can be used for renegotiating the task in case of machine breakdowns or other unexpected events (Sousa and Ramos 1999). In that case, the task holon will be informed by the resource holon where the event originated, and will begin negotiations for the operation(s) previously contracted to that resource with other resource holons following the same steps previously described. At this time, if rescheduling is not possible, the task will be completely abandoned, and a manual scheduling of that task must be engaged.

4. Operational description of main holons

The key entities participating in the scheduling process (activity chosen as the test case) are the physical resources and the manufacturing orders. These two entities are represented in the system by resource holons and

task holons respectively. This section details the internal behaviour of each one of these holons.

4.1. Task holon

A task holon represents a manufacturing order to execute a certain quantity of a specific product on the shop floor. This kind of holon has as its objective to schedule the order and monitor its execution.

Its life cycle (figure 3) begins when the manufacturing order is created (either to fulfil a customer order or to balance stocks). During its existence the task holon will negotiate with resource holons the execution of the operations needed to perform the ordered product. The holon will cease existing when the order is fulfilled or cancelled.

After obtaining information about the order, the task holon negotiates with resource holons using CNCPP. The holon will then wait for the bids and evaluate them, in order to select one (if possible). If it is not possible to schedule the order, the task holon will recombine the resources and perform a new negotiation. A renegotiation may also be necessary if the order's condition changes e.g. anticipated due date, delayed, etc. (Sousa and Ramos 1997, 1999). The evaluation of bids is performed taking into account a prioritized list of criteria. The following criteria have been implemented in the prototype: (i) first valid solution; (ii) least costly solution; and (iii) greatest slack till due date. The cost of a solution is determined by the cost of performing the specified operations in a specific resource.

4.2. Resource holon

A resource holon represents the current state of a physical resource on the shopfloor. The resource's list of activities is called agenda, stating what to do and when. The resource is able to perform operations

necessary to execute products (e.g. drill). A resource holon can represent a single resource or a work cell composed of several resources.

The objective of a resource holon is to control the physical equipment, provide information about its abilities and status to the system and manage the scheduled activities. Its life cycle is very long, since it is

expected that a resource is fully operational for long periods of time. During its existence, the resource holon executes the commands sent by the resource controller and negotiates with task holons the scheduling of manufacturing orders.

During initialization, the holon builds its initial agenda, registers in the directory service and holarchies to which it belongs (e.g. scheduling, process planning). The negotiation process of the holon is guided by the execution of the CNCPP state machine (figure 4) for each conversation currently taking place with task holons. Upon reception of a service request (for the possible execution of one or more operations) the resource holon will check its availability and engage in negotiation with other resource holons for propagating constraints between the operations. After calculating its feasible intervals for each request, it will send a bid and wait for the task holon's reply (accept or decline). There is a cost mechanism associated with operations and resources, such that a resource holon replies to a task holon with a bid specifying the price (in abstract units) of performing that operation.

Figure 3. Task holon's life cycle.

5. The prototype suite

5.1. Prototype description

Figure 5 presents the Fabricare scheduling prototype suite, composed of several applications. The 'configuration

Figure 4. State diagram for one negotiation.

Figure 6. Production plans for test scenario 1.

Table 1. Test conditions for test scenario 1.

Resource	Operation	Duration	Initial agenda
M1	op1a	2	[(5, 7), (11, 13), (18, 20)]
	op3b	1	
	op1c	2	
M2	op2a	3	[(8,10), (15, 18)]
	op1b	2	
M3	op3a	1	[(1, 5), (16, 19)]
	op2b	1	
	op2c	1

Figure 7. Results of test scenario 1.

Another experiment was made considering a task with a sequential production plan (op1 op2 op3) for the production of two items. The initial agenda for each resource as well as the cost associated with each operation for the several resources are presented in table 2.

This experiment considers the existence of alternative resources for the realization of op1 (R1 and R4) as well as for the realization of op2 (R2 and R5), hence generating four alternative solutions shown in table 3. Furthermore, the cost of executing an operation varies according to the resource it is performed in.

The selection criterion used was 'least costly solution', which eliminated the first two proposals. The other two proposals have identical costs (and identical schedules

since R5 had no initial commitments), thus the task holon used the 'first valid solution' criterion as secondary selection criterion, resulting in the following assignment (including slack): R4/(6, 10), R2/(7, 21) and R3/(10, 24).

For relatively simple production plans (maximum five operations) with some alternatives (maximum eight alternative plans) the performance obtained was quite good since solutions were given (on average) in less than 1.10 seconds. The test bench consisted of a network of Microsoft Windows workstations and the results were measured from the control panel component and include network latency and communications overhead – thus this is the system response time from the user point of view. These results allow expecting a convergence of solution considering soft real-time constraints. Obviously, more complex production plans and several alternative resources may produce an exponential explosion of the solution space and resulting in the degradation of the system performance.

6. Conclusions and future work

This paper presented a system based on holonic concepts and a prototype implementation of that system that may be characterized by:

- The main entities in the manufacturing systems are represented as holons while the core functions are represented as holarchies.
- It is a distributed application based on the multi-agent and holonic paradigms.
- The implementation of task holons and resource holons (as well as other support holons) for the dynamic scheduling of manufacturing orders.
- The knowledge and control of each agent is separated through holon scripts.
- It is open and flexible in which concerns the number of holons.
- The holons have the ability to represent and handle incomplete information in their knowledge bases.

Table 2. Test conditions for scenario 2.

Resource	Operation	Duration	Cost	Initial agenda
R1	op1	1	100	[(1, 2)]
R2	op2	1	100	[(6, 7)]
R3	op3	3	300	[(7, 10)]
R4	op1	1	90	[(1, 2), (3, 6), (10, 12), (17, 18)]
R5	op2	1	100	[]

Table 3. Results of test scenario 2.

Solution	Cost	Resource	Proposed intervals	Partial cost
R1-R5-R3	1,000	R1	[(2, 20)]	200
		R5	[(3, 21)]	200
		R3	[110, 24]]	600
R1-R2-R3	1,000	R1	[(2, 20)]	200
		R2	[(7, 21)]	200
		R3	[(10, 24)]	600
R4-R5-R3	980	R4	[(6, 10), (12, 17), (18, 20)]	180
		R5	[(7, 21)]	200
		R3	[(10, 24)]	600
R4-R2-R3	980	R4	[(6, 10), (12, 17), (18, 20)]	180
		R2	[(7, 21)]	200
		R3	[(10, 24)]	600

This system resembles the distributed nature of manufacturing, thus allowing for a better modelling of the real system. While other co operative communities operate with agents representing resources or systems, the Fabricare system combines resource-based holons with task-based holons. The main advantage is the easy access to task activities that are supported in task-based holons as well as high adaptability to the dynamic nature of resource conditions and availability.

The negotiation protocol presented to regulate the interaction among the several agents in the system contract net with constraint propagation protocol (CNCPP), may be characterized by:

- Explicit cooperation phase between service providers (i.e. resources) motivated by the need to coordinate temporal relations of a task's operations.
- Dynamic participants, using the information of running agents stored in the directory service.
- Conflict avoidance by serializing overlapping negotiation (concurrent time-windows for different resources/tasks).
- The existence of alternative resources for the same operation may cause combinatorial explosion of the solution space.

- The number of exchanged messages is of the order $O(n)$.
- A renegotiation phase can be triggered by abnormal events (e.g. machine breakdown).

The main advantage of this protocol is the existence of explicit cooperation between resource agents in order to guarantee feasible schedules satisfying the precedence relations between operations in the same task. One of the major issues for future work is the combinatorial explosion of the number of generated solutions. A possible solution for this problem may be to guide the selection process of the task holon by applying meta-rules based on the complexity of the problem and the available time. This has the side effect of introducing soft real-time constraints in the protocol to ensure at least one solution in useful time.

The scheduling procedure (intimately related to the protocol just described) was adapted from a proven centralized method, but introduced the following new characteristics:

- Use of a distributed approach with several computational processes (resource holons and task holons) performing partial calculations and having partial problem data.
- Use of cost by operation by resource which allows a new parameter to obtain different solutions.
- Possibility of several resources for the same operation generating several alternative schedules considering resource's agendas and costs.
- Use of buffers between resources allowing for greater flexibility than with the static behaviour model.

The main advantage of this scheduling procedure is the fact that it allows the use of several resources for the same operation and allows for greater flexibility by not using behaviours as in the original method.

Thus, it is possible to say that the Fabricare system achieves the objectives stated in section 1 in the following way:

- *High flexibility* – since the structure of the system is 'open and flexible' the number of resources may vary, with resource holons being added or removed on the fly. Furthermore, additional functionality can be introduced at each resource. Task holons use a dynamic query to find out which resources to negotiate with, thus getting a snapshot of the system at that specific time instead of relying on a static *a priori* mapping of the world.
- *High adaptability* – since there is some support to a renegotiation phase in the CNCPP, the system may adapt to abnormal events. However, there is still some work to be done in this matter: for instance,

introduce some notion of priority or budget to the task that will allow it to 'persuade' other scheduled tasks to give up resource time in order to fulfil its schedule.

- *High availability* – since there is no central control element in the system, single points of failure do not exist which makes the system more robust to workstation or network breakdown. Additionally, having duplicated functionality in different resources allows the system to continue operating using the remaining pool of resources.

The problem being addressed here is related to the ability to build and maintain computer-supported manufacturing systems able to cope with recent (and expected future) requirements, giving the social-economic context of the new digitized, customized, global society. In a way, the answer to this question can be given by organizing the manufacturing system into 'small' units structured according to the holonic theory.

Essentially, it is argued that in order to overcome the rising customization of goods and services as well as other trends in society and economy, it is necessary to build systems with such characteristics as: distribution, decentralization, autonomy, dynamism, reactivity, flexibility, adaptability and agility. Although current manufacturing systems do not present them, this kind of properties can be found in holonic systems. These were the principles and goals guiding the development of the Fabricare system.

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