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Holonic implementation of the open-control paradigm*

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Abstract

In the context of FMS, where products and resources entities can be seen as active, this paper presents the open-control paradigm and gives an example of its instantiation with holonic scheme. The open-control concept, developed in our Lab, exhibits the classic explicit control, as well as an innovative type of control called implicit control. The implicit control allows system entities to be influenced via an Optimization Mechanism (OM). After introducing the open-control paradigm, we illustrate one possible implementation based upon an holonic approach and applied to a job shop production system, containing multiple networked robot workstations. Implementation architecture and first experimental results are reported.

Key words: open-control, flexible manufacturing systems, holonic manufacturing system

1 Introduction

To be competitive, manufacturing should adapt to changing conditions imposed by the market. The greater variety of products, the possible large fluctuations in demand, the shorter lifecycle of products expressed by a higher dynamics of new products, and the increased customer expectations in terms of quality and delivery time are challenges that manufacturing companies have to deal with to remain competitive. Besides these market-based challenges, manufacturing firms also need constantly to be flexible and adapt to newly developed processes and technologies and to rapidly changing environmental protection regulations.

In recent decades, scientific developments in the field of production have defined new architectures including the heterarchical/non-hierarchical architectures that play a prominent role in FMS. This paper presents the open-control paradigm and the reasons for developing it (sections 2 & 3). An instantiation of this paradigm using the holonic manufacturing concept is presented (section 4). This paradigm is an extension of the previous work in the domain of heterarchical control [10] and includes the concept of implicit control in addition to the traditional explicit control.

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2 Motivations

In this paper, the term “control” includes what is generally accepted as the whole loop, from sensors to actuators. As a result, a closed loop can then be identified as something that exists between a system that controls and a system that is controlled [14].

Traditional approach is mainly associated to the initial CIM (Computer Integrated Manufacturing) concept and usually leads to centralized or hierarchical control structures. Due to the complexity of manufacturing problems, the usual practice has been to split the overall problem into hierarchically-dependent functions that operate within decreasing time-ranges, such as planning, scheduling and/or monitoring. This traditional approach is known to provide near optimal solutions, but only when hard assumptions are met, for example, no external (e.g., urgent orders) or internal (e.g., machine breakdowns) perturbations, well-known demands, and/or supplier reliability. Since reality is rarely so deterministic, this approach rapidly becomes inefficient when the system must deal with stochastic behavior.

The above observations have led researchers to define a second approach to designing control architectures. These control architectures, also called emergent or self-organized, can be categorized in four types [2]: bionic & bio-inspired, as proposed by Okino [8] and Dorigo & Stützle [3]; multi-agent, as proposed by Maione & Naso [7]; holonic, as proposed by Van Brussel et al. [12]; and heterarchical, as proposed by Trentesaux et al. [9]. An analysis of the state-of-the-art has been recently published by Trentesaux [10]. His main conclusion is that the expected advantages of such architectures are related to agility: in the short term, such architectures are reactive and in the long term, they are able to adapt to their environment. However, these last control architectures suffer from the lack of long-term optimality, even when the environment remains deterministic, which can be called “myopic” behavior. This is the main reason why such control architectures are not really used by industrialists at the moment.

The aim of this paper is to propose a global control paradigm, called "open-control", in which traditional control is augmented by a new kind of control: “implicit control”. In this paradigm, entities can be strictly controlled hierarchically and, at the same time, they can be influenced heterarchically by their environment and/or by other entities. This paradigm would make it possible to design control systems that are both agile and globally optimized, thus reducing the myopic behavior of self-organized architectures and increasing the agility of traditional architectures. Combining the two types of control in the same architecture creates new challenges since the two types of control must now be managed and integrated within the larger control paradigm. The following section describes the “open-control” concept in more detail. In addition, this paradigm has been designed to integrate control approaches from different communities that are usually opposed from each other such as CIM community (computer integrated manufacturing), HMS community (holonic manufacturing system), MAS community (multi-agent systems) and biological-inspired community (ants colony, etc.). This integration will then create new opportunities to hybridize all these approaches.

3 The open-control concept

3.1 General framework

We propose a control framework in which an entity can not only achieve its goal in terms of the system objectives but also in terms of its own objectives. An entity can be a resource or an active product. An active product is an entity that able to inform, communicate, decide and act in order to reach its goals in solving resource allocation and routing problems. (For more details on the typology and advantages of active products, see Zbib et al. [16].) Figure 1 shows a general view of this framework.

As shown in Fig. 1, this framework has various levels: level i serves the level i+1 above it and is served by level i-1 below it. This figure proposes a classic time horizon view, with long term problems being solved at the top and real-time problems being solved at the bottom. In this framework, autonomous entities can exist in both the physical and informational worlds.

In typical Flexible Manufacturing Systems (FMS), the physical world is made up of the physical parts of the entities, which range from passive products (e.g., a pure raw product) to a resource's raw materials (e.g., the mechanical structure of an assembly robot) and, by extension, to the Human Operator's body, which is the special case of a non-artificial entity. The informational world is usually composed of 3 control levels (1 to 3): strategic problem solving at the top (level 3), operational problem solving at the bottom (level 1), and tactical problem solving in the middle (level 2). For example, in classical FMS, ERP (Enterprise Resource Planning) would be on level 3, MES (Manufacturing Execution System) would be on level 2, and Automation & PLC (Programmable Logic Controller) would be on level 1.

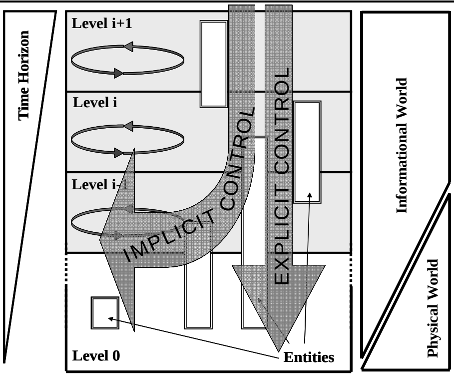

Fig. 1. General control framework.

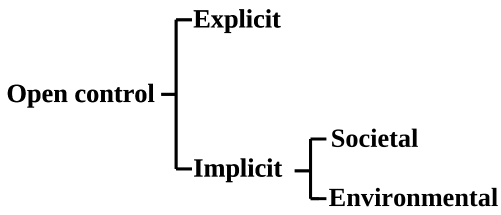

Fig. 2. Control typologies.

Agents, like those found in Multi-Agent System (MAS), are purely informational entities, while raw materials are purely physical entities. Holons and Intelligent Physical Agents (IPA) are examples of intermediary entities, capable of existing in both the physical and informational worlds. In FMS, the usual term for intermediary entities is "Holon" (introduced in 1967 by Arthur Koestler [5]), specifying that the system is one in which certain entities have a physical and informational nature, thus conserving the system's recursive nature.

In our framework, each control level has an optimization mechanism, symbolized by the looping arrow at each level in figure 1. In a system composed of autonomous entities, each entity is immersed in an informational level orchestrated by an Optimization Mechanism (OM), and each entity is always trying to achieve its own objective through decision-making that is influenced by either a societal or an environmental OM (see 3.2). Each entity is free to achieve its own objective, but in terms of global system performance criteria that apply to all entities. In general, the system must be used by all entities and must work for all entities.

Figure 1 shows two kinds of control:

- Explicit control, in which the entities at each level are linked to entities on a higher level through an obligatory control relation (e.g., master-slave),
- Implicit control, in which the entities at each level are influenced by an OM but not necessarily controlled.

Thus, generally, entities must achieve their own objectives, possibly by being explicitly controlled or perhaps by being influenced by an OM. The next section presents a more detailed description of the different aspects of our open-control concept system, notably the implicit control through the influence of societal and environmental OM. Figure 2 shows the control typology referred to in this paper.

3.2 Implicit and explicit control

Before describing in detail the explicit and implicit control used in our paradigm, we must first introduce a model of an advanced FMS control based on the framework shown in Fig. 3.

<u>Description of the Advanced FMS control model</u>: Fig. 3 represents an advanced FMS in which entities (e.g., resources, active products) have decisional capacities (represented by D in a circle) and thus play an active role in achieving their goals.

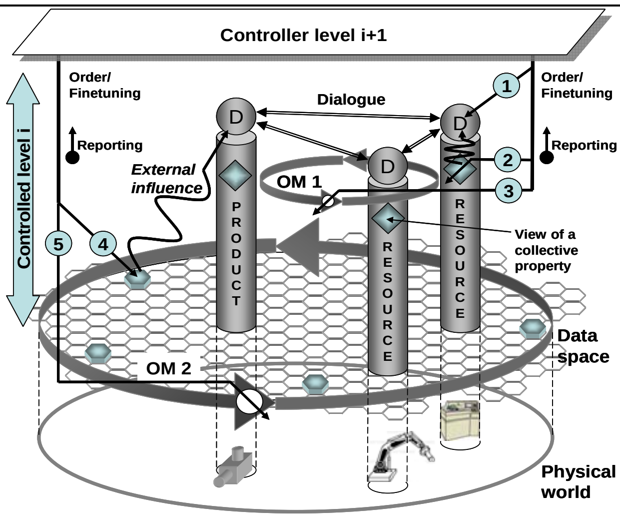

Fig. 3. Advanced FMS control model.

In Fig. 3, the two main levels of our framework are represented: the controlled level i, in which the different entities evolve, and the controller level i+1, which controls level i. The physical world is also represented through the physical base of the different entities.

As mentioned above, each entity must meet its own goal but in terms of collective global performance criteria. At their individual levels, the entities all have a self-made view (personal knowledge) of the collective performance criteria (represented in Fig. 3 by a small diamond). This partial view is achieved by dialogue among entities. For example, in a classic contract-net approach, an active product can dialogue with the resources and thus obtain a view of the availability of the resources and choose the most appropriate. These exchanges will support a mechanism for optimizing collective performance. In the following, this first type of optimization mechanism (OM1 in the figure) is called societal, because it only concerns the entities and not directly their environment.

The entities also have access to an informational environment, composed of data spaces placed in certain locations (represented by small blue hexagons in the figure). The entities can access the information available in their vicinity and integrate this information into their decision-making. The entities can also enrich the data spaces with their own experiences. These experiences may correspond to a collective performance criterion. For example, in routing applications, marks located on the nodes of a graph can be used to provide a view of overall traffic fluidity; the entities' travel experiences can thus be used to update these marks.

The informational environment (labeled data space in Fig. 3) is dynamic and governed by positive and negative feedback. These two types of feedback compose the second type of optimization mechanism (OM2 in the figure), called environmental. For example, Ant Colony Optimization (ACO) studies use diffusion and evaporation laws, inspired from the real ant colonies, to solve discrete optimization problems, as routing in graphs [3]. Diffusion laws use positive feedback to spread information throughout the environment, while evaporation laws use negative feedback to update data and/or remove outdated data.

<u>Explicit control</u>: Explicit control involves a classic top-down, master-slave approach to control: a controller sends orders to a specific clearly identified subordinate (arrow #1 in Figure 3). This subordinate sends information in return. As in classic automatic control, the explicit command of an entity can be achieved in two ways: by modifying the input and/or by finetuning the parameters. For example, the controller level might decide to stop a specific resource in order to perform routine maintenance or it might change the priority of a work-in-progress product.

Implicit control: Implicit control involves influencing entity behavior by the finetuning the parameters of the optimization mechanisms. This type of control works in two stages. First, through top-down order or finetuning, the controller level directly affects an intermediate entity that plays a role in a societal or environmental optimization mechanism. Then, an information exchange (peer-to-peer dialogue or a diffusion process) influences the behavior of the other entities on the same level.

- Implicit control via a societal OM This kind of implicit control can be performed in two ways. The first involves finetuning the partial view of a collective property inside an entity (arrow #2 in Fig. 3). This modification can be seen as an internal influence that modifies the entity's behavior. This behavioral modification then influences the other entities via the societal optimization mechanism, which is supported by dialogue. For example, the controller can force a specific product type to be machined on a specific resource, which implies changing the dynamic of the allocation process for the other products. The second way involves changing the dynamics of the dialogue in the societal optimization mechanism (arrow #3 in Fig. 3) by modifying the dialogue parameters inside the entity. For example, in a contract-net context, a product can interrogate all the resources or only those resources in its proximity. This second way has a direct impact on the overall collective performance.

- Implicit control via an environmental OM This kind of implicit control is performed via the informational environment in two ways: the first (arrow #4 in Fig. 3) involves acting on the data directly (e.g., creating, updating, erasing), while the second (arrow #5 in Fig. 3) involves finetuning the parameters used by the environmental optimization mechanism. Both actions generate an external influence that can affect all that entities able to access the informational environment. For this type of implicit control, no communication between the entities is required.

The main difference between implicit and explicit control is that, in implicit control, the final entity is not directly targeted. Implicit control uses a dedicated intermediate, which does not directly target the influenced entities. This type of control is very interesting for applications which involve multiple entities that can not be controlled directly.

3.3 Application to usual FMS control architectures

To validate the applicability of our generic Open-Control paradigm, we applied this to three FMS control architectures (see figure 4).

- Classic CIM architecture (on the left side of Figure 4): in this type of FMS, the entities on the lower level have no decisional capacities. The products are totally passive and resources are directly subordinated to the upper control levels. Resource planning and scheduling are organized in a hierarchical control structure, using only explicit control. The entities do not have their own goals and have no vision of the global collective performance. The different optimization processes are performed on the upper control levels according to different time horizons.

- Holonic architecture (in the middle of Figure 4): Holonic manufacturing systems (HMS), a research direction proposed by the Intelligent Manufacturing Systems consortium, transpose the concepts developed by A. Koestler [5] for living organisms and social organizations to the manufacturing world. Holonic manufacturing is characterized by autonomous and cooperative entities, called holons, which represent the entire range of manufacturing entities. A holon, as devised by Koestler, is an identifiable component of a system that has a unique identity, yet is made up of subordinate components, and in turn is part of a larger whole [6]. The HMS concept is widespread, particularly due to the success of the reference architecture, PROSA, proposed by Van Brussel et al. [12]. For more details on recent researches in HMS field, see for example Ulieru and Norrie [11], Baïna and Morel [1], Verstraete et al. [13], Hsieh [4]. A detailed description of a holonic system applying our open-control paradigm is presented in section 4.

- Stigmergic architecture (on the right side of Figure 4): This FMS architecture is based on the stigmergy concept, which describes a mechanism of spontaneous, indirect coordination between entities. Marks left in the environment by an action facilitate the completion of other successive actions. In this architecture, the control is totally implicit and the informational environment supports the optimization mechanism without necessitating dialogue between the entities.

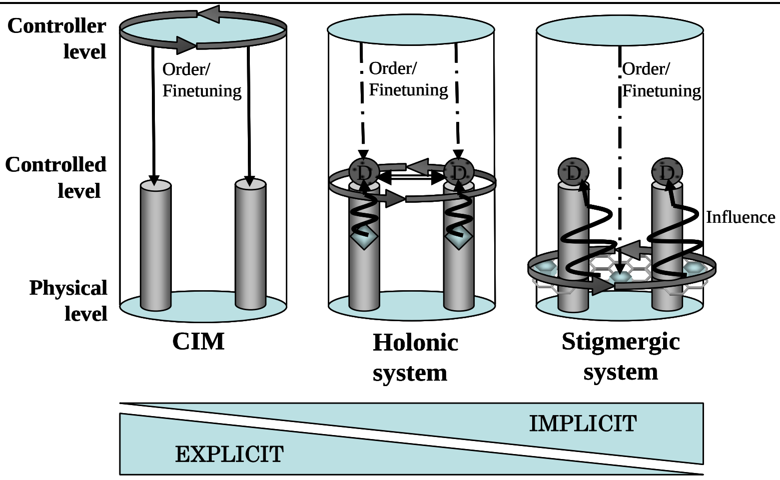

Fig. 4. Control architectures comparison using the open control paradigm

4 Open-control applied in a holonic manufacturing system

In this part we present the instantiation of the open control paradigm to a HMS and its application to a real production cell. The studied cell is first described. The holonic architecture is then explained and the instantiation of the open-control paradigm is pointed out. Last, results are provided to illustrate this application.

4.1 Production cell description

The holonic control mechanism is being developed in the frame of the RVHOLON (Robot Vision Holonic Manufacturing Control) grant [15], at the University Politechnica of Bucharest. This manufacturing cell (job shop type) is composed of five networked robot-vision stations (Fig. 5). The five robotic stations are interconnected by a Bosch Rexroth TSplus closed-loop twin-track, pallet-based power-and-free conveyor with four linear bidirectional derivations, that move subassemblies fixed on pallets in single or double access production stations, from W5 (loading/unloading station) to: W1, W2, W3, and W4 robotized workstations (capable to execute several operations). Figure 5 shows location of each production station Wi, and shows that several networked SCi controllers and a PC computer support the automation level.

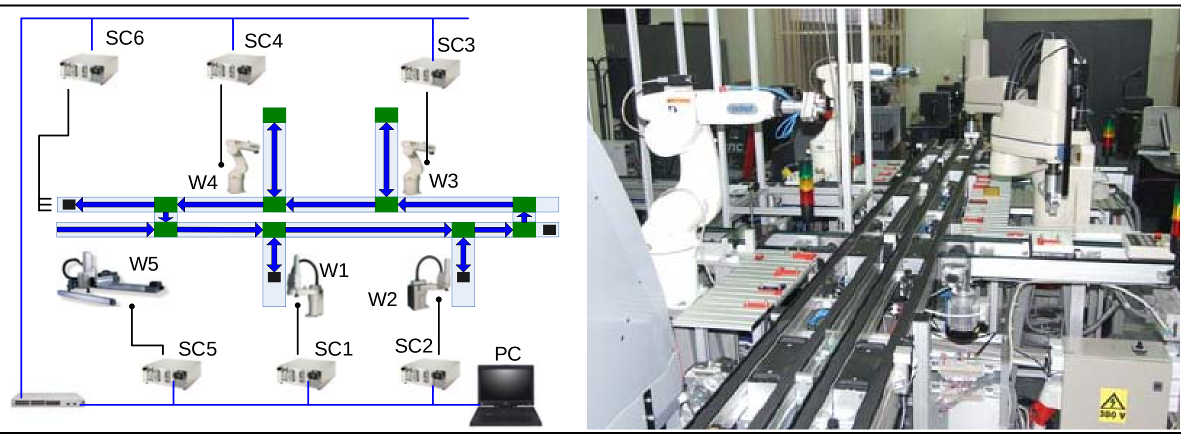

Fig. 5. The production cell with networked robotized workstations: layout (left) and realization (right)

4.2 Holonic architecture

From a general point of view, an FMS is composed of orders (products to be executed) and resources (entities that act upon products in order to be executed). In reference with the PROSA architecture [12], there are three major types of holons aimed to provide production control: resource holons, product holons and order holons. The data structures representing these three holons contain the following information:

- *Order holons* are characterized by information of the following types: identifier, production information (operations to be performed, the production plan), planning support information (these are variables indicating the state of the real concerned product at different time moments).

- *Resource holons* contain the following information: identifier, operations that the attached physical resource is capable to do, state of the resource.

- *Product holons* contain: the identifier of the physical product, a list of operations to be executed on this product, the precedence of the operations to be executed, the necessary materials and resources, the programs and the parameters needed to execute the operations.

In this holonic context, we have spotted two types of resources RP and RR holons: - *RP holons*, which transform an order holon into the desired product, - *RR holons*, which transport an order holon through the system to the processing resources.

By instantiating the general advanced FMS control model (Fig. 3), and taking into account the interactions between resources and orders, we defined the following architecture, figure 6. This figure exhibits three levels:- physical level, with physical parts of products and resources,- automation level, which supports data (personal knowledge) and processing (decision making) by mean of PC for "real products/order holons", and SCi Controller for each resource (RP: Processing Resources and, RR: Routing Resources),- MES level, which fixes production demands. All communication, among resources and "real products/order holons", are supported by an Ethernet industrial network.

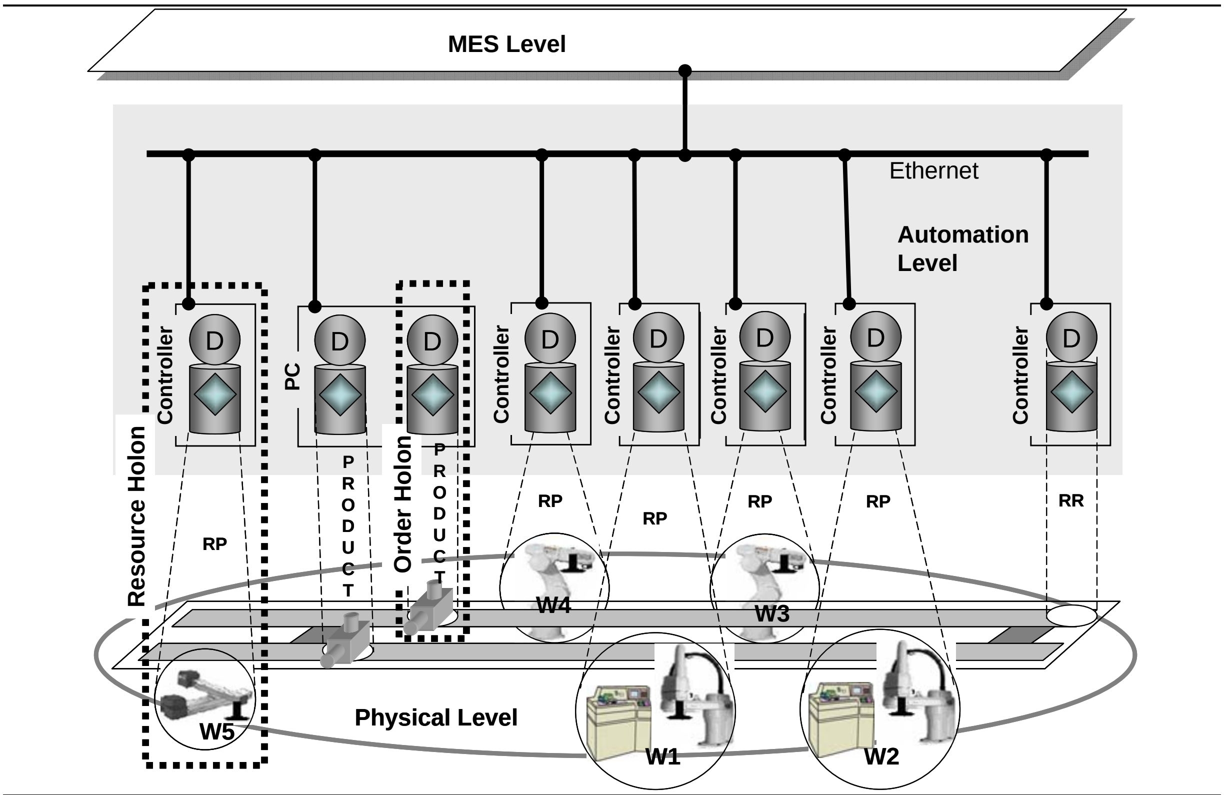

Fig. 6. Holons in the job shop-type FMS and their localization according to the open-control model

Each order holon must choose the path through the fabrication system, what operation? what RP holon? what RR holon?, last two questions being considered together in order to minimize the sum of the processing and routing times. According to the above description the execution process is composed of the three following sub-processes: - First, an order (seen as an active decisional product) *updates its personal knowledge* (A) described by the diamond in figure 7 about the possibilities of each resource from the system ; - Second a *decision* (B) is taken that regards the three questions posed above (operation, RP & RR resources) ; - Final step, *execution* (C) takes place.

The whole process is described in Fig.7 as a general flow.

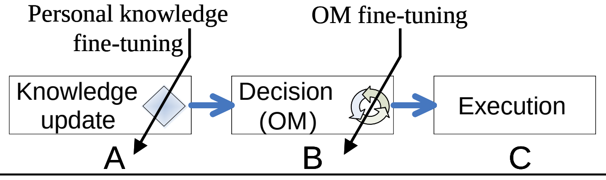

Fig. 7. General order execution process

4.3 Instantiation of the Open Control concept

Like each instantiation of the open control paradigm, we must define what kind of control can be considered as explicit or implicit.

In this instantiation using the holonic approach, explicit control concerns direct action on different holons. By example, the upper MES level imposes a product blue-print for an order in terms of processing operations.

Holonic approach assumes also a kind of implicit control. In this instantiation, we chose a societal OM that can be fine-tuned by two ways :

- The information in the personal knowledge can be increased or decreased, so the order holon has better or worse perception of the global system in terms of performance resources (capacity, availability, workload...). Exchange between the order holon and resources can equally be influenced. For example, an order holon, to increase its knowledge, can exchange with all resources or only nearest. The arrow on the diamond (Fig. 7) illustrates this.
- The OM is based on a multi-criteria decisional process and can be fine-tuned in modifying decision rules, weight of each rule... (illustrated by the oblique arrow on the loop OM (Fig. 7)).

The next section exhibits first experimental results.

4.4 First experimental results

In the first preliminary trials, four operations can be performed on the different resources according to the following distribution: W1 {op1, op2}, W2 {op1, op2}, W3 {op2, op3, op4} and W4 {op1, op3, op4}. A number of four types of products have to be manufactured; their operations belong to the operation set {op1, op2, op3, op4}.

Given all this process information, several batches have been launched to test the correctness of the system and the maximum number of pallets that it can contain: each product was produced in a batch of 100 pieces and the timing results are shown in the graphic below (Fig. 8).

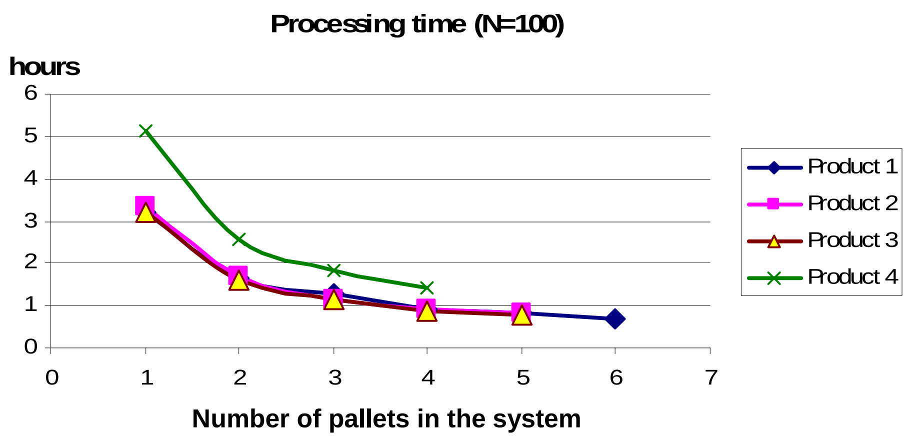

Fig. 8. Execution time as a function of the number of pallets for 100 products of the same type

For a small production, i.e. with a number of order holons comparable to the maximum number of pallets coexisting into the system it can be seen that a minimum time is achieved for a maximum number of 6-7 pallets simultaneously present in the system. The total processing time decreases with the number of the pallets coexisting in the system (Fig. 8). This decrease depends on the product type and the distribution of operations on the resources, but if more than 6 pallets are simultaneously in execution, the risk that the conveyor gets blocked increases. This happens because there might be pallets on the main belt waiting to enter workstations (Wi), and pallets with products just processed and leaving the stations to reenter the main belt at the same moment of time.

The first results presented in figure 8 confirm the correctness of the job scheduling societal OM and the good behavior of the global system. However new test campaigns must be performed to improve the holonic approach and to compare the obtained performance results with those of a classical hierarchical control. Nonetheless, the aim of this paper was mainly to show how the holonic paradigm can be effectively seen as an instance of a more global paradigm called open-control. That also means that other studies must be made to evaluate more precisely other kinds of instantiations of FMS control architectures, especially hierarchical, (CIM), multi-agents, bio-inspired approaches and so on. This is one of the main short-term perspective of our work.

5 Conclusions

In this paper, we have presented our open-control paradigm and have show that it can be instantiated with the holonic approach. In addition, the designed holonic architecture has also been validated on a real production cell to verify its consistency. Of course, a complete validation procedure must be realized (comparison with other control architectures on a benchmark…), but this is in fact beyond the scope of this paper. Short term perspective concerns then the validation of the open control paradigm on other classes of control architectures (CIM, MAS, bio-inspired…). Concerning middle term perspectives, we are now working on a design method that will help designers to specify their open-control architecture models exhaustively, thus informing them in advance all the properties inherited from his design choices and the set of commonly encountered issues to be solved.

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