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PRODUCTION SCHEDULING IN A HOLONIC MANUFACTURING SYSTEM USING THE OPEN-CONTROL CONCEPT

Silviu RĂILEANU[1]

Dezvoltările prezente din domeniile tehnologia informației şi electronică au permis trecerea de la un control clasic centralizat către un control descentralizat. În acest context prezentul articol propune un nou concept de control în care comenzile de la un nivel superior sunt tratate ca recomandări, în timp ce entitățile de pe nivelul controlat comunică între ele pentru a rezolva şi optimiza sarcinile primite ca recomandări. După introducerea conceptului de control, va fi prezentată o implementare care vizează planificarea producției folosind o abordare holonică. Această implementare a fost realizată pe un sistem de producție de tip job-shop cu posturi de lucru interconectate.

Current advances in information technology and electronics allowed the passage from the classic centralized control approach to a fully decentralized control approach. In this context the paper proposes a new control concept in which the commands from a superior control levels are sent as recommendations and low level entities communicate between them in order to solve and optimize the task given as a recommendation. After introducing the control concept, an implementation aiming at production scheduling using a holonic approach is illustrated. The implementation was done on a job shop type production system containing multiple networked workstations.

Keywords: Open-control, holonic manufacturing systems, Contract Net Protocol

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 to be constantly flexible, adapt to newly developed processes and technologies and to rapidly changing environmental protection regulations, support innovation and continuous development processes [11].

[1] Phd student, Faculty of Automatic Control and Computer Science, University POLITEHNICA Bucharest, Romania, e-mail: silviu@cimr.pub.ro

Although the optimization of the production process remains a key aspect in the domain of fabrication systems, adaptive production gains more and more field [15]. Flexible manufacturing systems should be able to quickly adapt to new situations like machine breakdown, machine recovery due to physical failure or stock depletion and also face rush orders [2].

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 is an extension of the work in [13], describing an instantiation of the societal implicit open-control, using the holonic manufacturing concept. This paradigm is an extension of the previous work in the domain of heterarchical control [16] and includes the concept of implicit control in addition to the traditional explicit control.

In recent years research has been done towards defining new control architectures, called emergent or self-organized. These architectures can be categorized in four types [4]: *bionic & bio-inspired*, as proposed by Okino [12] and Dorigo & Stützle [6]; *multi-agent*, as proposed by Maione & Naso [10]; *holonic*, as proposed by Van Brussel [18]; and *heterarchical*, as proposed by Trentesaux [17]. An analysis of the state-of-the-art has been recently published by Trentesaux [16]. His main conclusion is that the expected advantages of such architectures are related to agility: on short term, such architectures are reactive and on 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 structure of the paper is: introduction of the open-control paradigm and its description in section 2, a detailed description of the static model of the fabrication system using the holonic concepts is presented in section 3; Section 4 presents the production scheduling and execution model. The paper ends with the experiments done and their results and conclusions and perspectives resulted from the current work.

2. Open-Control Concept

The work in this paper focuses on a new type of control in which an entity tries to achieve its own goals with respect to the global system objectives through dialogue with the other entities; the entities can be resources or active products, both equipped with decisional and communicational capacities. An *active product* is an entity that is 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 [20]).

The control principle described above will be further called in this paper *open-control*, according to [14], because of the capacity of subordinate levels to receive orders from upper control levels through direct orders (explicit control) and recommendations (implicit control), in which case they exhibit local decisional capabilities to follow their own objectives enabling thus the easy addition and removal of entities.

Based upon the relations between different control levels, Fig. 1 shows the two kinds of control: the explicit control, in which the entities from lower levels are subordinated directly to entities to a higher level through a strict control relation (e.g., master-slave) and the implicit control, in which the entities on lower levels are influenced through an intermediary optimization mechanism but not necessarily controlled. 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.

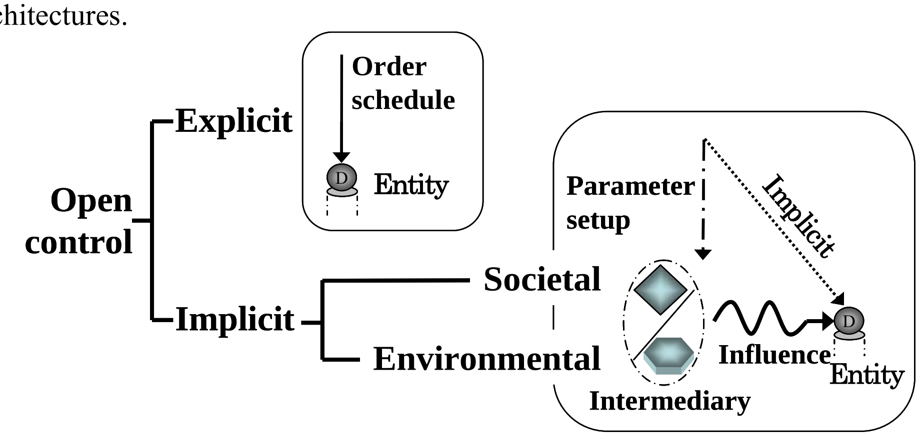

Fig. 1. Control typologies present in the open-control concept

Implicit control involves influencing entity behavior by setting up the parameters of the optimization mechanisms. This type of control works in two stages. First, through explicit control, the superior level directly affects an intermediate entity that plays a role in a societal or environmental optimization mechanism. The affected part of the intermediary entity can be either the decisional mechanism (represented by the diamond in Fig. 1) which generates a societal type of control, or it can be a directly the environment which memorizes information (represented by the hexagon in Fig. 1). Then, an information exchange (peer-to-peer dialogue or a diffusion process) influences the behavior of the other entities on the same level. Taking into account the way the upper control level influences the lower levels, implicit control is of two types:

I. **Implicit control via a Societal Optimization Mechanism (SOM)**. In this case the upper level either fine-tunes the partial view of a collective property inside an entity, modifying its behavior and then this entity influences the others through dialogue, or the upper level changes the dynamics of the dialogue in the SOM by modifying the dialogue parameters inside the entity. The key element of implicit control using SOM is the dialogue between entities which leads to the two characteristics of holonic manufacturing systems: autonomy and cooperation [9]. This is why this concept offers good means of implementation for semi-heterarchical control systems which under normal conditions works like a hierarchical structure (Ex.: staff holon proposed in PROSA, [18]), but when perturbations take place each entity uses its own decisional capacities to continue production.

II. Implicit control via an Environmental Optimization Mechanism (EOM). This type of control is performed using last minute information from the environment [3]. This environment is characterized by a memorization mechanism, which stores data or physical characteristics, and an optimization mechanism that acts upon the memorized information modifying it in time.

3. Holonic model of the fabrication system

Based on the PROSA reference model [18] and the production domains presented in [11] the following base elements were identified in a fabrication system: resources, products (blueprints) and orders in execution represented by the physical products which are currently fabricated. Because the entities in the fabrication system are almost all equipped with decisional capabilities it has been decided to structure the system according to the holonic principles and implement an implicit societal open-control which will confer both the adaptive and optimality characteristics in its operation. The following elements, presented in Fig. 2, have resulted after applying the holonic scheme to the flexible manufacturing system: resource holons (RH), product holons, order holons (OH) and expertise holons (staff holon according to PROSA).

The **order holon**, the first key point of the fabrication system, represents the client's order in real-time and is composed of the following informational and physical parts: an augmentation module which enriches the holon with decisional (information processing), communicational (information transport) and memorization (information storage) capabilities , the pallet which associates with the fabricated product along the production phase providing it transportation services and the passive product which is fabricated/assembled on the pallet. The structure of an order holon emphasizes the recursive propriety of a holon which can in turn be composed of other holons. In this case the order holon contains two resource holons, a pallet used for transportation with an augmentation module used to process information, and a product holon representing the blueprint containing the operations needed for execution.

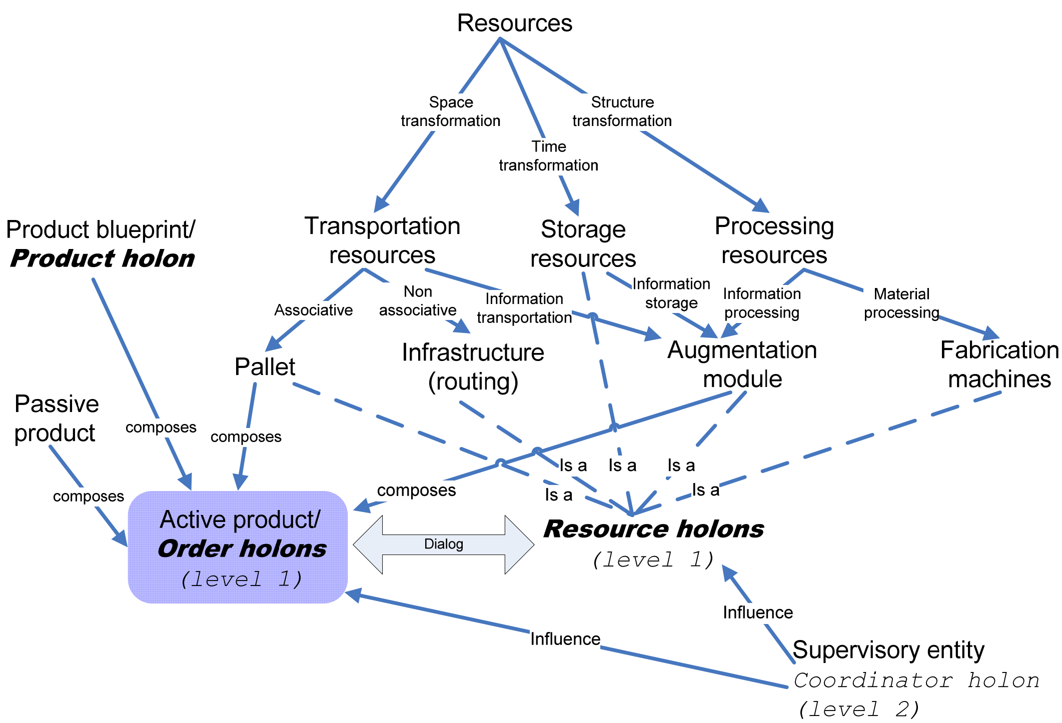

Fig. 2. System components (static model)

Depending on the way the order holon connects to the informational network (RFID, WiFi, IrDA, etc) and the computational capacities of the local augmentation module the OH intelligence can be divided as follows (Fig. 3):

1. At *distance*, on a distant machine: in this case between the main control system and the physical part (the pallet) a synchronization exists so that the control system is always aware of the current state of the product. Usually this is done using RFID. In this case the OH is delimited by line 1 in Fig. 3;
2. *Locally*: the main control system is located directly on the physical part. In this case the OH is delimited by line 2 in Fig. 3;
3. *Hybrid*: the main control system runs on a distant dedicated machine and its role is to take high level decisions (ex.: processing resource allocation). Besides this high level control system there is a local control system dedicated to handling alarms, monitoring product status and taking local decisions like routing towards a goal established by the main control system. In this case the OH is delimited by line 3 in Fig. 3.

The second key point of a fabrication system, the **resource holon**, is composed of an informational part responsible for decision making, control and communication and a physical part responsible with the physical processing (e.g.: mounting a piece on the product, image recording, etc). Depending on the type of operation performed by the resource the system is composed of the following basic types of resources: of processing type offering structural transformation services, of transportation type composed of motion infrastructure (ex.: conveyor belt or conveyor segment) and mobile entities (ex.: mobile shuttle/pallet) which together offer spatial displacement services and storage type offering time locating services. Moreover, each resource can be further classified, according to the entity upon the function is exercised, into information processing (as is the case of the augmentation module) and material processing (as is the case of an industrial robot working upon a product).

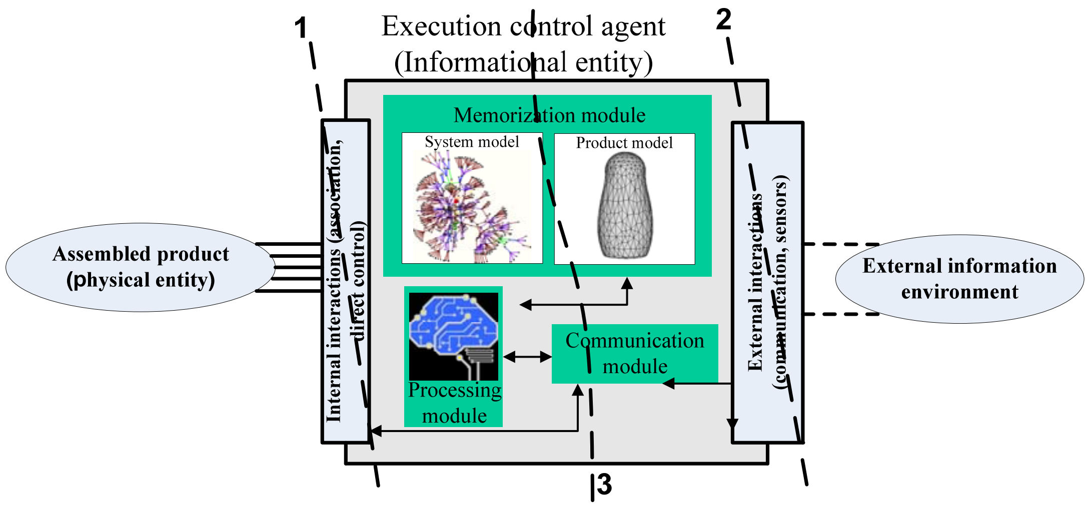

Fig. 3. Location of an OH intelligence

For the logical part of the system to be in conformity with the societal open-control concept proposed, the entities of the system are distributed on a 2 layer architecture, a low decisional level and a high decisional level. Usually a factory is composed of three levels [14]: strategic problem solving at the top (level 3), tactical problem solving in the middle (level 2) and operational problem solving at the bottom (level 1), our architecture taking into account level 1 and 2.

The low decisional level (level 1) is composed of autonomous entities, OHs and RHs, which communicate in order to optimize their production schemes. The high decisional level (level 2) role is to provide general guidance, through the influence of the Optimization Mechanism (OM) existing at level 1 (Ex.: explicitly modifying the local view of an entity, like the set of corresponding entities to communicate with), in order to attain a global objective; otherwise the low decisional level might have an uncontrolled emergent behavior. The high decisional level is represented here by the coordinator holon which besides general guidance offers a mean of integrating the fabrication system into the upper layers of the factory (Ex.: attaching client demands to order holons, supervision of the system, computing parameters describing the global behavior of the system, etc).

4. Production scheduling and execution model

Although an FMS is composed of transportation, processing and storage resources, for fabricating a product only the processing resources are mandatory; the others are just used to automate the transportation process. For this reason when executing a product the decisional module should provide an answer to the following questions: What is the next operation? What is the resource that will do that operation? How do I bring the product there? The last two questions are being considered together in order to minimize the sum of the processing and routing times. According to Fig. 4, the general order execution process is composed of the following three subprocesses:

- First, an order (seen as an active decisional product) *updates its personal knowledge* about the possibilities of each resource from the system (A);
- Second, a *decision* that regards the three questions posed above is taken (operation, **R**esource for **P**rocessing (RP), **R**esource for **R**outing(RR)) (B);
- and third step, *execution* (C) takes place.

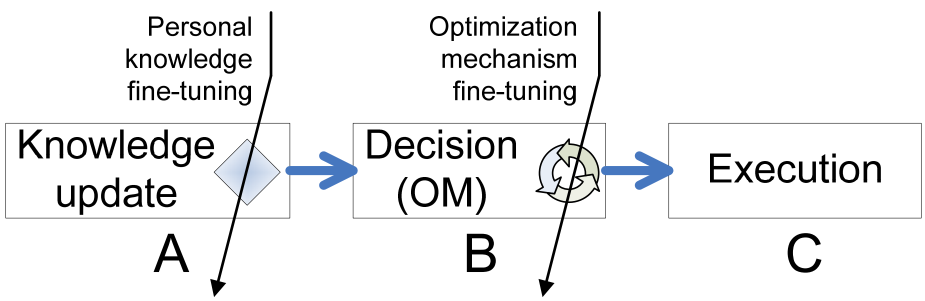

Fig. 4. General order execution process

The extended process is a modified version of the Contract Net Protocol [8] and is described in Fig. 5.

Fig. 5 presents the dynamic interaction of the decisional entities presented in Fig. 2 for optimizing the allocation and execution operations according to the implicit type of control. The choice for the product to be manufactured is done by the augmentation module in a fixed location, the input/output of the system. Once a product is chosen it cannot be changed unless its production was completed or it was compromised in the manufacturing process. In order to find out what type of product should be attached to the pallet, the augmentation module interrogates the client’s orders database, then the system resources and then, according to the products deadlines, to their complexities and also to the charge of the system a single product representing a production order is chosen for fabrication.

The interaction process between an OH and the RHs, representing the dialog arrow in Fig. 2, begins with the "knowledge update" stage during which each order operation is tested to see if there is a corresponding resource capable of executing it. Then, for each resource found capable of executing a processing operation a path towards it is searched. The knowledge update process takes place two times, first for the processing model and second for the routing model.

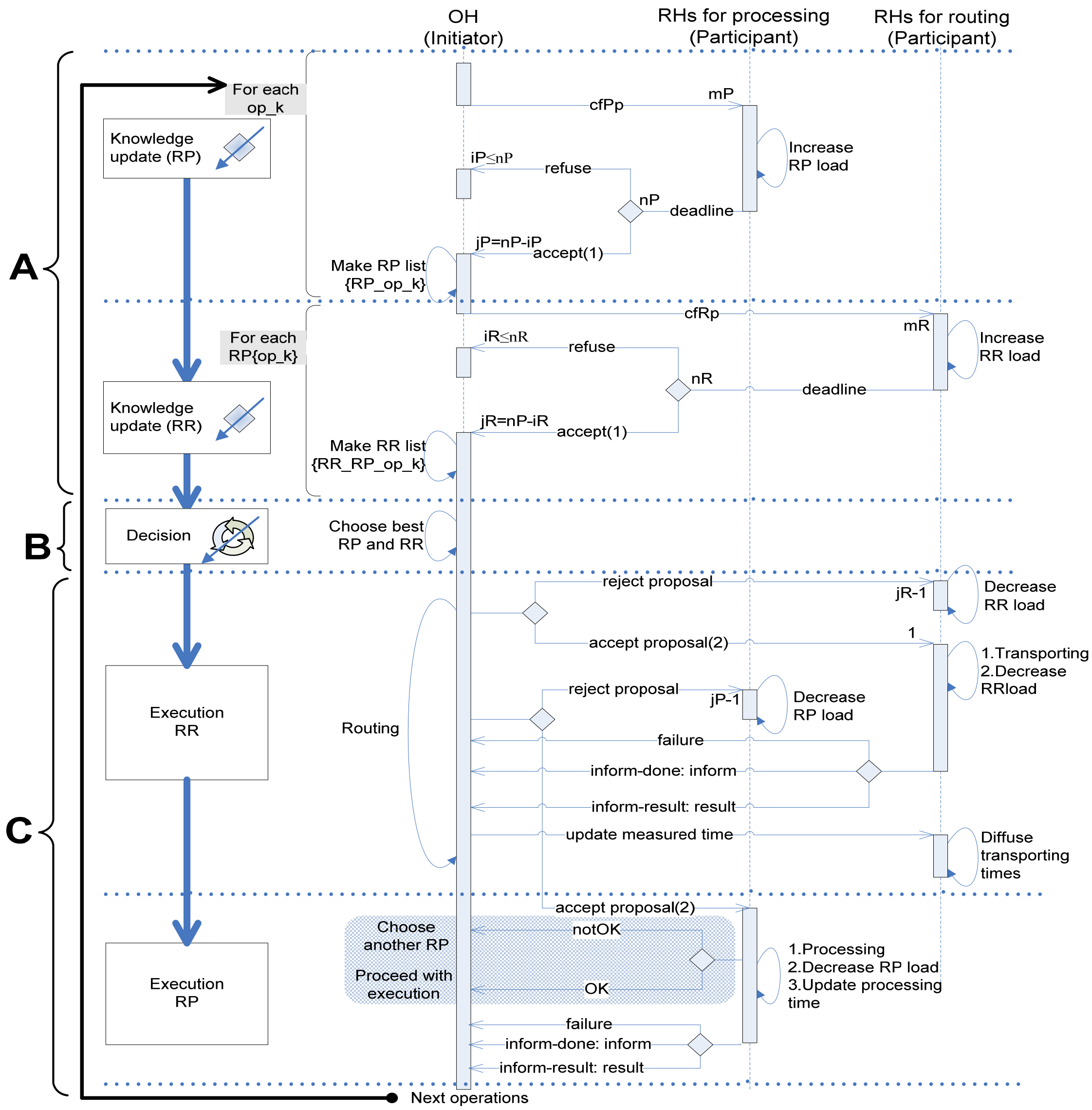

Fig. 5. Interactions between order holons and resource holons for optimizing the allocation and execution operations

The messages to resources are sent in the form of call for proposals (*cfPp* referring to calls made for processing resources and *cfRp* referring to calls made for routing resources). If the resource does not respond in an established interval it is declared off-line. If the resource replies in this interval the answer can be negative or positive. The negative answer represented by the *refuse* arrow in Fig. 5 indicates that the state of the resource does not permit to execute the requested operations because the resource is busy with other products, or the resource can not execute the requested operations; in both cases the resource is operational. The positive response is represented by the *accept* arrow that indicates the availability of the resource to execute the requested operation.After the "knowledge update" process the model of the system is ready and the production order can begin taking decisions which regard the manufacturing process: what is the next operation, on what resource it's done and what is the path to the resource.

After the above decisions are taken, the workloads of the chosen routing and processing resources are increased. This process is represented on the diagram of the interactions in negative logic (to respect the standard Contract Net Protocol [8]), with the aid of the *proposal reject* message which is sent to all the resources that have participated in the dialogue and have not been chosen; in order not to increase and then decrease resource charge during each dialogue it was chosen to increase the charge only once, after the decision.

The start of an operation, routing or processing, is marked by the *accept proposal* message, which in the case of processing resources may contain additional parameters. Before the production order enters the processing resource a last dialogue takes place between it and the corresponding resource in order to confirm the production possibility. After the *accept proposal (2)* message, the chosen resource must send a message that contains either *OK*, the product can enter, or *notOK*, the resource has failed during the routing phase of the production order or another product is in production or there is no raw materials in the workplace, in which case the product jumps at the decision state, seeking another answer to the 3 above questions.

The end of an operation is marked by the reception of one of the following messages *inform-done* (operation well finished), *inform-result* (operation finished and status) *or failure* (operation failed).

For other production orders to take into account the transportation times in real-time (e.g.: instantaneous charge of a line between two resources) travel times are measured and then written to the destination transport resource with the aid of *update measured time* message; this time is then diffused to all the other transport resources via a broadcast mechanism.

The OM is done using dialogue between the entities of the system. The data exchanged in order to minimize the makespan is the charge of each resource.

5. Experimental results

5.1. System description

The open-control concept presented above was implemented and is currently under testing at the Flexible Manufacturing System at AIP PRIMECA Valenciennes, Fig. 6. The production cell is composed of a transportation system characterized by self-propelled and autonomous pallets, offline stations with a limited capacity and diverters that can be controlled by any entity through the PLC that it is associated to. Each station is equipped with a resource which can execute different types of processing operations upon the visiting product: automated assemblies (mount r, I, L, axe and screw pieces on products), visual inspection, loading and unloading products. Due to the redundancy of the transportation and processing resources the system possesses an important degree of flexibility at both transport and process levels (Fig. 6) which can be used in certain situations to optimize production by balancing operations among equivalent resource and assure a certain degree of fault tolerance.

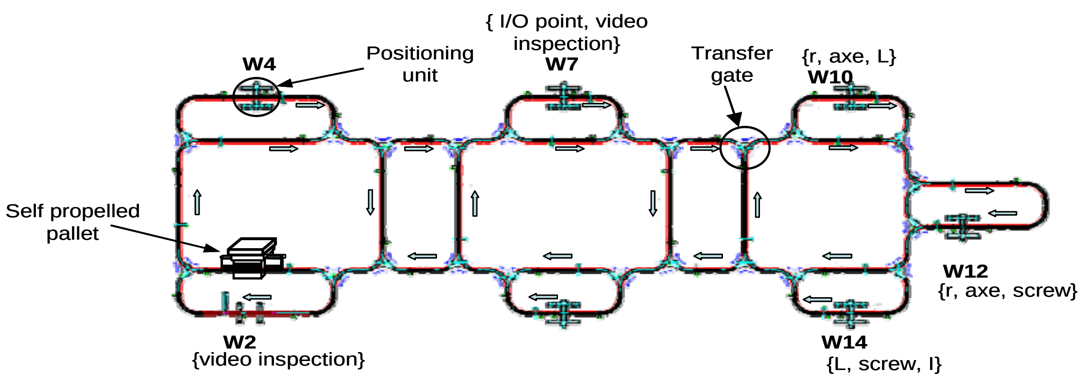

Fig. 6. AIP cell system layout and operations distribution

The transporting resources are composed of the underlying infrastructure on which the physical support of the order holons progress, along with the control represented by WAGO PLCs [19] that drive the transfer gates according to the commands received from the OH. The processing resources are represented by the corresponding resources and the PLCs that do the control, and consist of industrial robots. The interactions between resources and orders (Fig. 7) take place in special places and via an Ethernet-IrDA bridge which aids to both communication and localisation. In our case the bridges consist of IrDa Clarinet systems ESB 101 [5] located for the transporting resources before the transfer gates and for the processing resources in the station workplace.

Control is fully decentralized because decisions being taken by the order holons and afterwards these decisions are being put into practice by the zone controllers which are the PLCs that control an automation zone composed of diverters, start/stop commands to pallets and processing resources. All the PLCs are connected by an ETH network through which they synchronize between them.

The practical results achieved until now, *dynamic routing* and *resource allocation*, are satisfactory in terms of correctness of operations and stability of the system in face of disturbances such as perturbations jams on the transportation infrastructure or resource breakdown.

The implementation of the routing part from the general interaction scheme from Fig. 5 on the production cell was done as depicted in Fig. 7 making use of the MODBUS protocol which already exists on the PLC controlling the resources. On the down side there are the entities that participate at the dialogue, the order holons and the resource holons, and in the upper part an adaptation of the general dialogue, routing and allocation, in presented in detail in Fig. 5.

Before starting execution, or after finishing an operation the online allocation of the next operation takes place as depicted in Fig. 7. Afterwards, the routing towards the selected resource is done. When the OH arrives at a routing node, the following messages are exchanged for the routing purpose:

1. The OH transmits the measured time it took to travel from the previous node to the current one and the RH broadcasts it to the others RH updating in real-time the routing information;
2. Information about the current resource is read from its control PLC;
3. The transportation times are read by the OH, which updates its routing model and chooses the shortest path by locally applying the Dijkstra routing algorithm [7], work detailed in [20];
4. The OH sends a routing demand to the current RH which acts upon the transfer gate.

Types of products executed in the fabrication system (bELT) (Fig.6)

- b : load, axe, axe, axe, r, r, I, screw, visual inspection, unload
- E : load, axe, axe, axe, r, r, L, visual inspection, unload
- L : load, axe, axe, axe, I, I, screw, screw, visual inspection, unload
- T : load, axe, axe, r, L, visual inspection, unload

The maximum number of palettes in the system is 3 because this is the number of equipments for the moment. Nevertheless, the control system was developed in order to work with any number of pallets, this being restricted only by the communication infrastructure, which may become overloaded, and by the physical transportation infrastructure which can accommodate only a limited number of pallets.

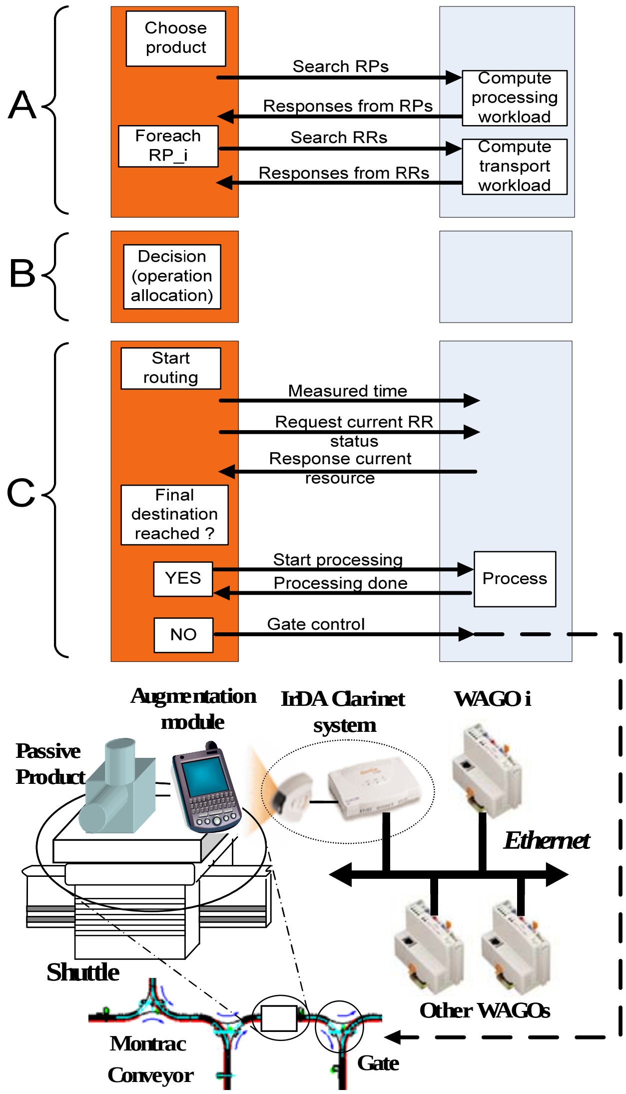

Fig. 7. System architecture and order-resource interactions for routing and allocation

5.2. Experiments

In this project it was proposed to prove by validation the capacity of the non-centralized holonic manufacturing system to adapt quickly and without external intervention to new circumstances and also optimize the fabrication by taking real time decision for routing and resource allocation. The scenario which will validate the above proprieties is the following: *Dynamic allocation* of production orders: our order holons are able to detect resources that are offline/not running and redirect themselves to equivalent resources if possible.

5.3. Results

Dynamic allocation

The processing times in each workstation are of 5 seconds. For this experiment 3 products of type b were used and launched as follows: the second is launched after the first leaves resource 10, after the resource is unplugged so the product has to do a dynamic reallocation to resource 12 which takes it more time as seen from Fig. 8 (the bar with a yellow flash is consistently longer then the bars with red triangles because the distance between resource 7 were the product starts and resource 12 is greater then the distance from 7 to 10).

From the figure it can observed that the makespan of the affected product is longer then the others 2 first because of the transportation time, which includes the resource breakdown detection and model update. To this it adds the dynamic allocation/reallocation of the vision operation [1] which has been done on resource 2. But, even without this the product would have taken a greater amount of time.

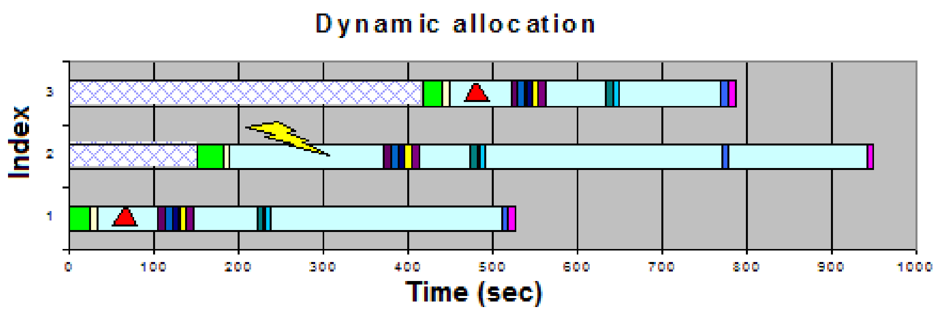

Fig. 8. Dynamic allocation GANTT chart

6. Conclusions and perspectives

In this paper it has been presented the societal open-control, a control paradigm well suited for decentralized FMS, which combines the advantages of "classical" control architectures (the possibility of hierarchical systems to achieve a global optimum) with the reactivity and easy maintenance, due to easy removal and addition of composing elements, of heterarchical systems. All these advantages come at a certain price in terms of extensive work and programming knowledge needed which are nevertheless justified if the designed fabrication system aims at an increased productivity and great flexibility.

Also, this tried to show that the open-control concept, and especially the implicit societal part, works very well into a holonic manufacturing system, since the proposed dialog between entities is key element of the holonic theory.

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