MANUFACTURING EXECUTION SYSTEMS FOR CUSTOMISED PRODUCTION

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Abstract. *Mass customised manufacturing is a current tendency in many production sectors. In this scenario, the client details the desired product often using informatics means and respecting available options. This customisation context imposes systemic integration and co-operations between the concerned manufacturing entities to explore their capabilities, aiming at adaptability to the product heterogeneity. An integration element of the management system and systems related to the shop floor is the Manufacturing Execution System (MES). A conceivable way to allow MES supporting this customised e-manufacturing is the concept of smart-product, where each product "drives" its own production, allowing a decoupling between production and order dispatching, as well as the consistency between physical and informational flows. A smart-product requires services from manufacturing resources and it can compete for them. These resources must co-operate based on their features and based on some established flexible co-operation logic, aiming to carry out smart-products requirements. However, this is by itself another issue, firstly due to the heterogeneity of factory resources. Looking for homogenisation and integration of this diversity, resources and also smart-products may be "encapsulated" inside of communicating entities called "holons". However, the composition of holonic MES (H-MES) is not trivial, because of the dynamic between all holons may be complex. Previous studies presented the organisation of Resource-HLs co-operation carried out by computational entities called "Rules". In this article, it is proposed a conceptual solution of a meta-model for Rules-oriented and product-driven H-MES and its application for the holonification of a design and simulation tool.*

Keywords*: Mass-customisation, product-driven control, H-MES, holonified simulation tool.*

1. INTRODUCTION

Nowadays the mass customisation is a tendency and a challenge to the intelligent manufacturing system (IMS) community(1)(2). In this mass customisation, customers make personal choices when they buy goods using no bureaucratic means, i.e. they want to buy products that correspond as well as possible to their needs and desires using the present technology easiness (e.g. e-commerce)(3).

Part of this thematic may be treated in the scope of Manufacturing Execution System (MES) whose primordial purpose is the integration of the management system and systems nearer of the shop floor operations(2)(4). A way to allow MES supporting this kind of customisation is to employ the concept of smart-product(2)(3)(6).

In a smart-product context, each product being processed is part of a smart-entity responsible for driving its production. This allows a better independence between the production and the dispatching of production orders. The smart-product also enables the consistency between physical and informational flows(6).

A smart-product must require services to manufacturing entities, e.g. resources as production-cells, equipment, and workers, aiming to reach its production needs. These resources could smartly organise themselves based on their own knowledge and on a flexible co-operation policy, in order to carry out the smart-products requirements. However, this co-operation is difficult, firstly because the elements of the factory are heterogeneous.

This diversity of resources could be homogenised and integrated by their encapsulation, in an abstract manner, inside of communicating entities called "holons" (HLs)(7). Hence, smart-products could be also holons able to negotiate with Resource-HLs or compete for them(6).

The composition of each product-driven holonic MES (H-MES) is not trivial, because the dynamic between holons can be complex, being necessary organisation means(6). Previous studies presented the organisation of Resource-HLs co-operation carried out by computational entities called "Rules" that allow establishing flexible co-operation logic(8)(9).

The Rules decide the good moments of co-operation based on the states notified from Resource-HLs. Rules can also requires services to them(10). In this context, each Product-HL can have its production needs appropriately carried out by Rules that it allocates(3). Therefore, the set of Rules is a decoupling mechanism to organise the Product-HLs and Resource-HLs co-operations.

The intention of this article is to propose a conceptual solution of a meta-model for product-driven H-MES. This solution is also used to improve a Design and Simulation Tool for Computer Integrated Manufacturing (CIM), called ANALYTICE II(5), in the direction of Holonic Manufacturing System (HMS).

A future objective is to present this meta-model as an engineering tool that allows aiding in the composition of similar systems, using a set of holons and its relationship previously developed and tested. The quality of the meta-model would allow reducing the time for system composition. In fact, this is already observable in ANALYTICE II context, where some experiments allow demonstrating the potential of the solution.

This paper is structured in the follow way to present this subject: section 2 presents the mass customisation issues and some rationales about smart production entities (holons), while the section 3 presents the HMS goals and the Holonic Control or H-MES needs. After that, section 4 presents the first efforts in the ANALYTICE II holonification, section 5 presents the solution to find a process-driven H-MES for it, and section 5 presents some relevant details of this holonic control solution. At last, sections 6 a 7, respectively, present the improvements of this solution for product-driven control and experiments carried out.

2. SMART-ENTITIES TO MASS CUSTOMISATION ISSUES

For dealing with variant production environment, manufacturing organisations must exploit their own existing flexibilities. The current researches in manufacturing system propose to use auto-organised entities in this context to improve the classical manufacturing process, where the autonomous production entities articulate themselves to produce (11)(12).

In classical manufacturing process, the production is planned in lots, by means of systems as Enterprise Manufacturing Planning (ERP), based on previous client demands. For a production planned in lots, the manufacturing entities (e.g. controllers and resources as machines) are prepared and fixed to produce few types of products, during a defined period. This policy is not interesting in manufacturing organisation aiming to solve mass customisation issues because, for example, the response time to treat customisations could be too long for a concurrent market context.

A solution to improve flexibility could be each order, e.g. concerned to a specific product instance, being an autonomous agent or smart entity. This smart-entity would know the capacities and states of robust resources, i.e. resources with a certain flexibility and re-configurability features, and it would launch itself in the production environment when appropriate.

The resources could be also "improved" with some expertise to allow smart-orders consulting their states and capabilities as well as to allow smart-orders requiring services. In practical terms, this would be implemented by a software entity or agent connected to the mechatronic physical resource, via computational-electronic means (Figure 1 adapted from Hartley[13]). The physical resource and its concerned agent are considered together a smart-resource.

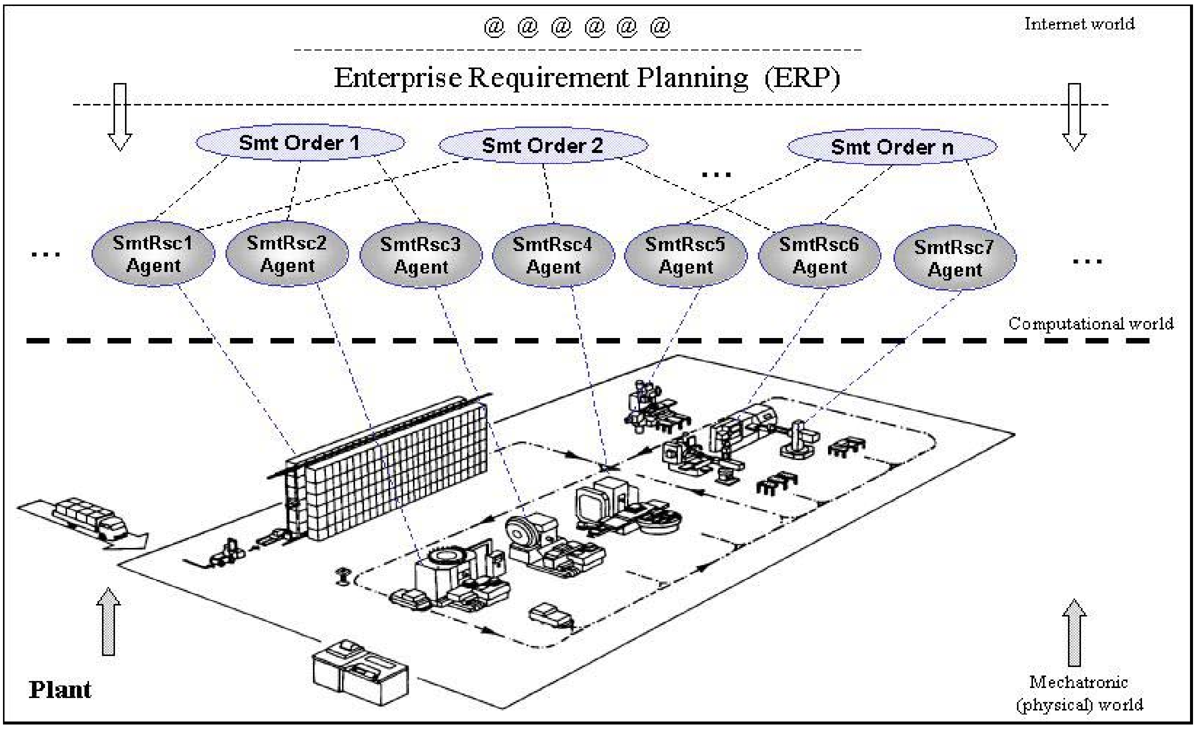

Figure 1. Integrated environment with Smart-Resource (SmtRsc) and Smart-Orders

In this scenario, the smart-order can arrive in the system, negotiate with smart-resources, in the computational word, and launch themselves in the smart-production environment. This agent orientation facilitates co-operations because heterogeneous production actors are homogenised at software level as well as their negotiations.

The above described environment allows an order-driven production, but a set of question and problems remains, as the possible incoherence between the information flow (smart-order) and respective physical flows (products), e.g. an smart-order could believe that its respective product is in a place but it is not. A solution is the integration of informational (soft) and physical (hard) parts, where each smart-order is its respective product guaranteeing the flows consistence (Figure 2). The conjunction of hard and soft product parts had been called smart-product[6].

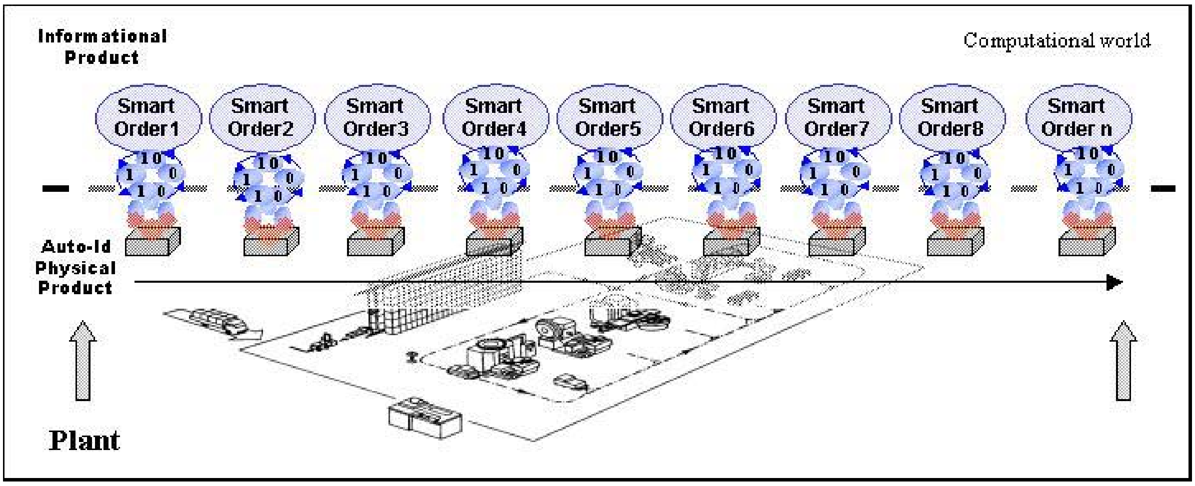

Figure 2. Smart-Product Holons, its hard and soft parts

For the implementation of a smart-product, in a technical vision, it is needed at least to identify the physical product with a certain frequency and force the update in the correspondent agent. The on-line trace of the product can be made using auto-id technologies, as RFID (Radio Frequency Identification). Also, some researches consider some smartness effectively in embedded system pasted in the product, using RFID technologies as communication means(6).

3. HOLONIC MANUFACTURING (EXECUTION) SYSTEMS

The concept of smart entity can be associated with the concept of holon from holonic system. A holon (HL) is currently defined as an autonomous and co-operative building block of a manufacturing system for transporting, storing and/or validating information and physical objects. A holon consists of an information processing part and often a dedicated physical processing part. A holon can be also part of another holon(7).

In the IMS researches about auto-organised systems(14), the most focused approach is the holonic paradigm originated from a philosophical theory on the creation and evolution of complex adaptive systems in the world (e.g. social systems, evolutionary theory). The main idea is to reach the good properties of holonic systems (e.g. adaptability and flexibility) in the manufacturing context, developing a class of system called Holonic Manufacturing System (HMS)(7)(12)(15).

Product-HLs and Resource-HLs negotiating in heterarchical way are not enough to reach the benefits wanted in the HMS. This could provide some problems, like states unpredictability, system deadlock or states explosion(6). Therefore, a control (like a Shop Floor Control - SFC) is necessary to intermediate or organise the Product-HLs and Resource-HLs negotiations, as well to control Resource-HL co-operations (Figure 3). However, this control must gives guaranties of operability to the system without impose a strong hierarchism, i.e. adaptability capacity must be preserved permitting a holarchy.

This envisaged holonic control is compatible with the industrial interests and researches in Manufacturing Execution System (MES), a SFC-like(4)(7). Therefore, this paper is in the context of Holonic MES, a research objective in the IMS community(2). In this sense, the next section presents the ANALYTICE II holonification as a contribution in HMS and HMES. Firstly, it is presented how to support Resource-HLs and how to develop robust process-driven holonic-control. After that, it is presented how to improve this solution to treat product-driven holonic-control and it is also presented some experiments.

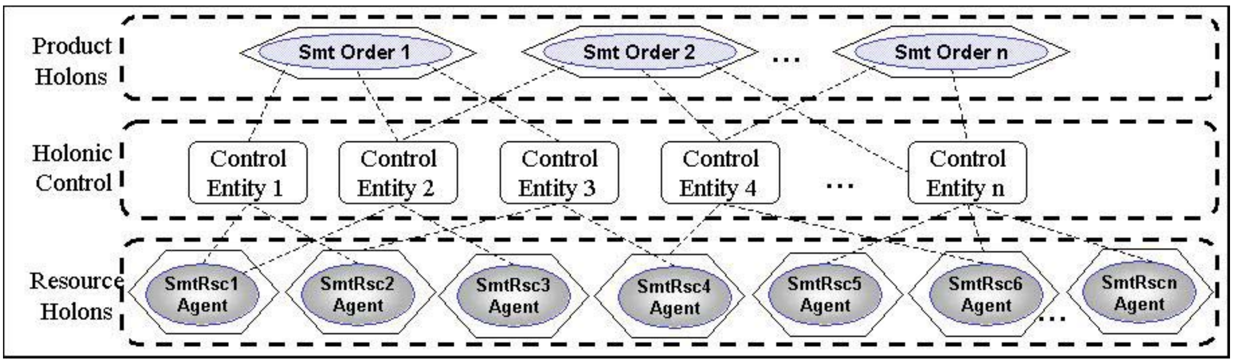

Figure 3. Holonic Control

4. HOLONIC SIMULATION ENVIRONMENT

At LSIP (*Laboratory of Intelligent Production System*) of the CPGEI/CEFET-PR a simulation and design tool for HMS is under development. This tool, called ANALYTICE II, was initially developed regarding CIM issues(5), but its primitives had permitted its holonification(3) (16).

ANALYTICE II has a clear separation between equipment emulation and the control execution, i.e. a layer that simulate entities like SCADA (Supervisory Control and Data Acquisition) and SFC (Shop Floor Control). This separation is forced by a virtual-network (Figure 4, left-side) that acts as the communication network between emulation and control sides(5).

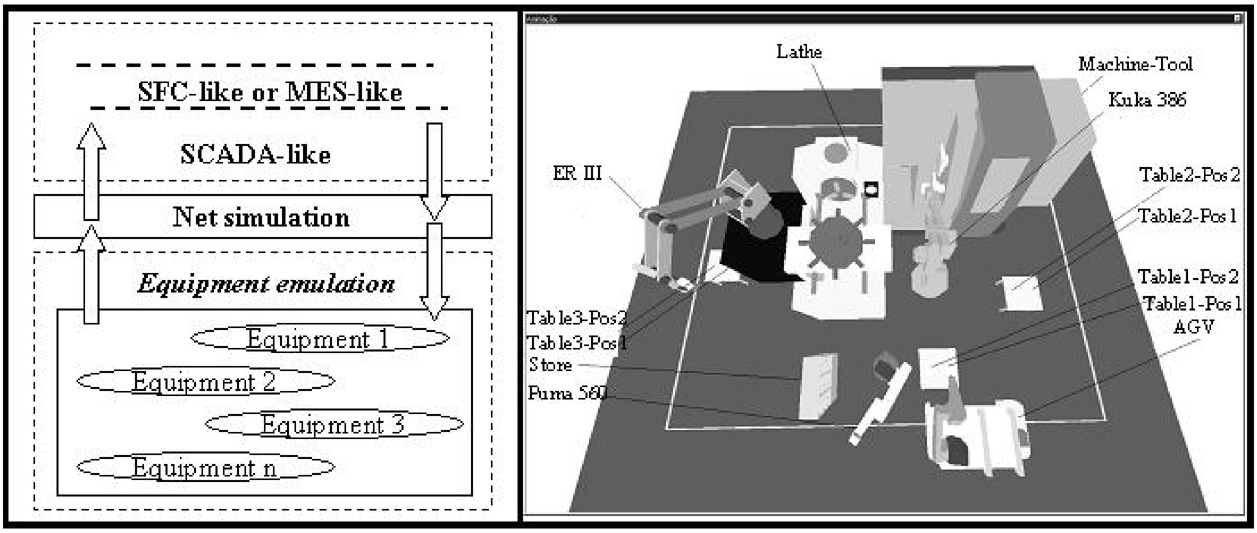

Figure 4. ANALYTICE II structure and its graphics animator module

An agent responsible for each equipment in the control side was proposed to ANALYTICE II holonification (Figure 5). This agent is responsible by receiving signals from the virtual-network relative to its respective equipment and by requiring services in a correctly parameterised way to the equipment also via the virtual-network. The agent can express the states of this equipment, in a high-way, by means of its subagents called Attributes and receive services demands, from other entities, by means of its subagents called Methods[8]. By this way, ANALYTICE II presents then Resource-HLs working in a homogenised way. In same way, the Resource-HLs substitute or improve the services concerned to SCADA layer.

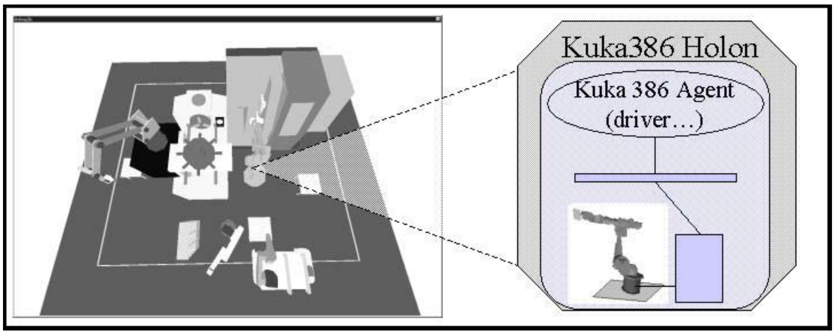

Figure 5. Example of Resource Holon in ANALYTICE II

5. PROCESS-DRIVEN HOLONIC CONTROL

The first experiments with holonic control in ANALYTICE II (Figure 4 and Figure 5) were made in the scope of process-driven control[9]. In process-driven control context, Resource-HLs already permit, for example, integration between high and low level of the manufacturing systems and the homogenisation of resources to be controlled.

A generic architecture was proposed to facilitate the design of control system to each experiment developed in ANALYTICE II. The main idea was to construct an architecture permitting to express and use causal relations to intermediate the co-operation between the Resource-HLs[8]. The solution proposed was inspired in Rule Base System (RBS), where each instances is a kind of Expert System (ES) to carry out the discrete event control (DEC) in a holarchy simulated in ANALYTICE II [9].

In fact, each control instance is similar to an ES whose base of facts is related to states of Attributes (inside of Resource-HLs), the decision and co-ordination is carry out by Rules and the final conclusion will be instigations of Methods (in Resource-HLs). The Rules and their associated entities (e.g. Premises and Methods) are computational agents or soft-holons. In Figure 6, it is presented an example of a Rule and its respective class diagram using UML (Unified Modelling Language).

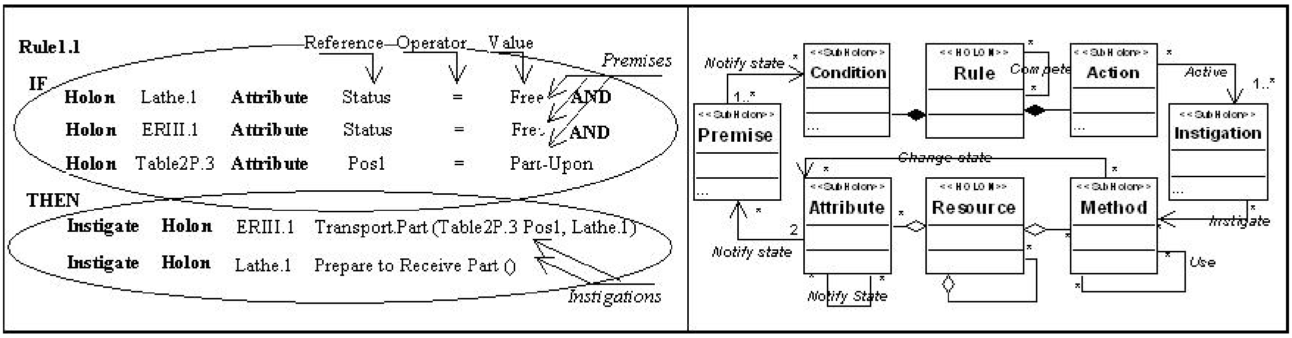

Figure 6. Rule and its associated entities

As an example, two control instances for a holonic manufacturing system designed in ANALYTICE II are described below.

In the system presented in Figure 4 (right side), it was simulated the production of virtual products of type X and Y. The process plan for X products is {<Store [pos1, 2, 3, 4, 5 or 6]> <Table 1 [pos 2]> <Machine-Tool> <Table 2 [pos 1 or 2]>} and for Y parts is {<Store [pos 7, 8 or 9]> <Table 1 [pos 2]> <Table 3 [pos 1]> <Lathe> <Table 3 [pos 2]>}. For co-ordinating the co-operation between the Resource-HLs, it was created a set of Rules allowing the production of X and Y products.

For this same system, the production of a real and pedagogic product was simulated. That product is related to a training context called AIPL (*Atelier Inter-établissements de Produtique – Lorraine*) associated to CRAN-UHP. The process plan to this product is {< Table 3 [Pos 1]> <Lathe> <Table 3 [pos 2]> <Table 1 [pos 1 or 2]> <Machine-Tool> <Table 2 [pos 1 or 2]>}.

For this case, a set of Rules was also used to control the Resource-HLs co-operation and statistical results were taken. Briefly, the system was productive in 83,68 % of time. This results means only that loading and unloading time between some resources must be optimised, i.e. the internal capacity of Resource-HLs. In the control point of view, the control had realised its function, i.e. to co-ordinate the Resource-HLs co-operation.

The Rule creation is based on the operations, and then on resources, necessary to each type of product. Pre and post time transformation (e.g. buffering) and space transformation (i.e. transport) are found to be linked to each necessary shape transformation (e.g. machining or inspection).

6. HOLONIC CONTROL STRUCTURE

A Rule aggregates a *Condition*, with connected *Premises*, and an *Action*, with connected *Instigations*. The *Premises* evaluate *Attributes* and *Instigations* activate *Methods*, and both *Premises* and *Methods* can be shared by Rules avoiding redundancies [9].

Each *Attribute* knows the *Premises* interested in its states changing and it straightforward notifies them when this occurs. Then the *Notified Premises* make a new logical calculus and each one whose state changed notifies the *Interested Rules*, which in turn recalculate their boolean values[9].

The agents-notification (Figure 7) is not only an elegant solution but also a contribution in inference process, eliminating search and bringing a quicker response or reactivity to the changes. Moreover, this mechanism had allowed proposing means to identify and resolve rules conflicts[16].

The elaboration of this generic-architecture, as a solution in holonic control, had particularities. Some considerations about good practices in system engineering were taken into account, as functional independence between the entities modelled[10] and trade-off between generality and applicability[16]. Furthermore, in the construction and evolution of this generic architecture or meta-model, beyond holonic concerns, control and computational concerns were considered.

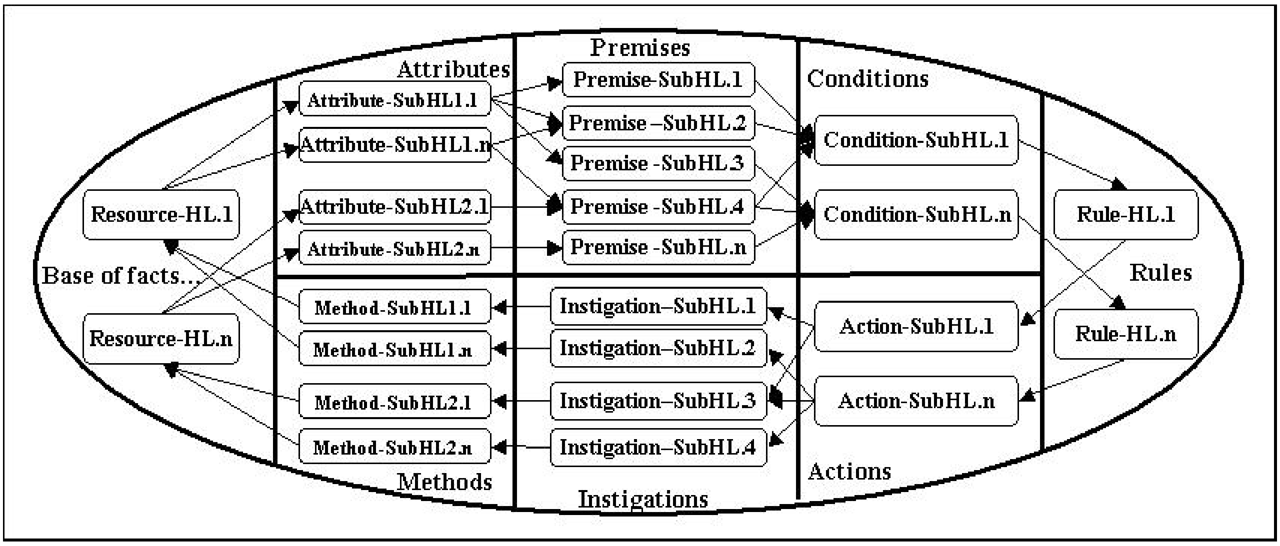

Figure 7. Notification mechanism

As holonic concerns, the adaptability of derived instances (e.g. exploit manufacturing system flexibilities depends of Rules knowledge), the human integration in the understanding or construction of the instances (e.g. Rules are intuitive) and the openness to systemic integration (as ERP integration by the Rule activation or deactivation depending on planned lots or orders) were considered.

In the scope of control concerns was considered, for example, the trade-off between determinism and reactivity, the conflict identification and resolutions (both facilitate by notification mechanism), and formalism (Petri net compatibility)[10].

In the computational concerns, it was considered question about direct openness to distribution and performance, i.e. notification and agent orientation and computational performances. The excellent performance is due to the avoiding of structural redundancies (via sharing of *Premises* and *Instigations*) as well as due to avoiding of temporal redundancies (via notification)[9].

7. PRODUCT-DRIVEN HOLONIC CONTROL

The solution to improve the proposed holonic control, as a product-driven control, is “simple”: Smart-Product-HLs will allocate the Rules according to its production needs (Figure 8). Therefore, a Rule will be enable to execute not only if it is true and some possible conflict is solved, but also if it is allocated by a Smart-Product-HL.

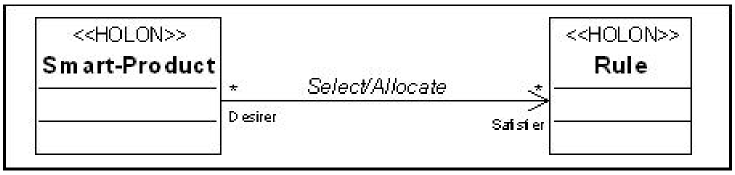

Figure 8. UML class diagram - meta-model upgraded for product-driven issues

Rules are created in agreement with operations need to produce the associated product-types, which could be the essence of holons (Product-Type-HLs) to create or considerate Rules, using appropriate algorithms. Thus, when a Smart-Product-HL is created, it could know good Rules for its production from the respective Product-Type-HL, and then appropriately allocate those Rules.

In ANALYTICE II, Smart-Product-HLs are only soft (as Smart-Order-HLs) because failures in the product flow are not generated yet.

8. STUDY CASES

The holonic control product-driven was tested in three cases. The first one was the same case of two virtual products presented in section 4. The observation was that the products could be putted in any place of the < Store >, because Smart-Product-HLs allocate the correct Rules to arrive in < Table 2 - pos1 > or < Table - pos2> depending of its type. This allows an independence of position pre-allocated in the store, i.e. it could be putted n ($n < 10$) products Y and m ($m < 10-n$) products X in the store, allowing a better buffer utilisation.

The second simulation relative to a real product (part type 01 in Figure 9) could be also carried out by means of a product-driven control. However, the results would be the same, because the process-plan does not present alternatives and there was only a type of product.

The second case study was a Flexible Assembling Cell (FAC). This FAC (Figure 9, right side) is the result of a pedagogical AIPL project, aiming to provide a real system for students apply engineering methods. It is a system to produce products adapted to pedagogy (Figure 9, "6 products type") while reflecting current industrial concerns.

The FAC is composed of six workstations (WSs), one for loading pallets circulating on a conveyor, four similar WSs for assembling products, and one to unload products on pallets (Figure 9). Each pallet is able to carry four products, and includes a digital memory able to store information about them. This FAC can produce six product types, from six part types(3).

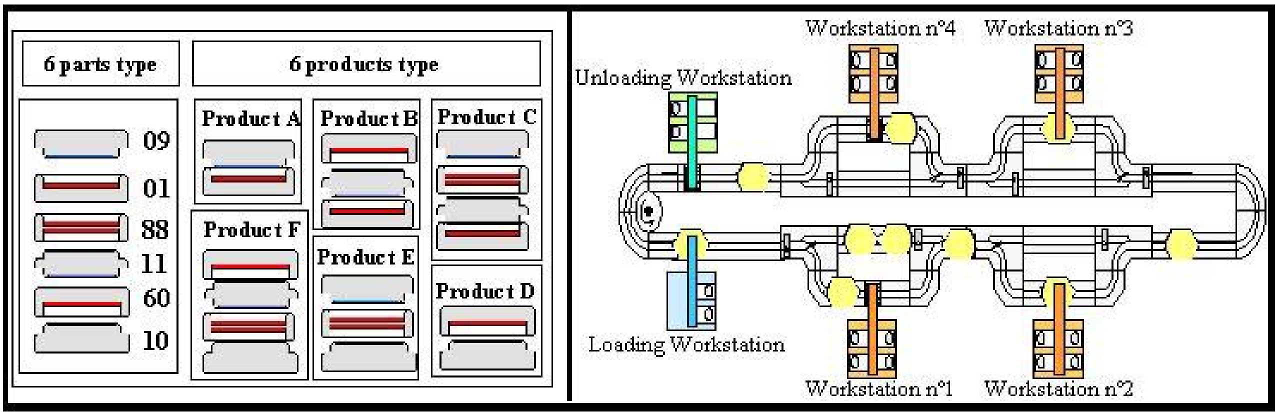

Figure 9 - The products related to the FAC (Flexible Assembling Cell)

By holonic models and some simulation efforts, it was observed that, in this case, the product-driven control could exploit the flexibility, for example: (a) Smart-Product-HL searching Rules to reach in alternative WS-HL when the aimed WS-HL is not available (e.g. very-loaded or semi-loaded if it is searched a WS balance) or (b) Smart-Product-HL allocating Rules to go out (under-loading the system) when Rules to production are not possible (e.g. if some WS-HLs are in failure state) and still notifying concerned systems to avoid the demand for production of this kind.

The third case study was a holonic hypothetical context inspired in the AIPL shop floor dynamics (Figure 10). The idea was produce 6 different kinds of products without previsions. Summarily, the H-FAC will assemble the products demanded just in time.

The Smart-Product-HLs are started and produced in the scope of FAC-HL, after that they search means to reach the Stock-Out-HL. When the FAC-HL stocks (in WS-HLs) are (or will be) lower than a limit established, a Rule is triggered creating a set of Base-Part-HLs (i.e. a kind of Smart-Product-HL).

Each Base-Part-HL will search Rules allowing it to be treated in the scope of Machining-Cell-HL (for machining), passing by the IUT-HL (for finalisations) and arriving in the WS-HLs (for buffering). Still, when the StockA-HL (with base-bars) is (or will be) lower than an established limit, a Rule concerned is triggered to create a Smart-Bar-HLs.

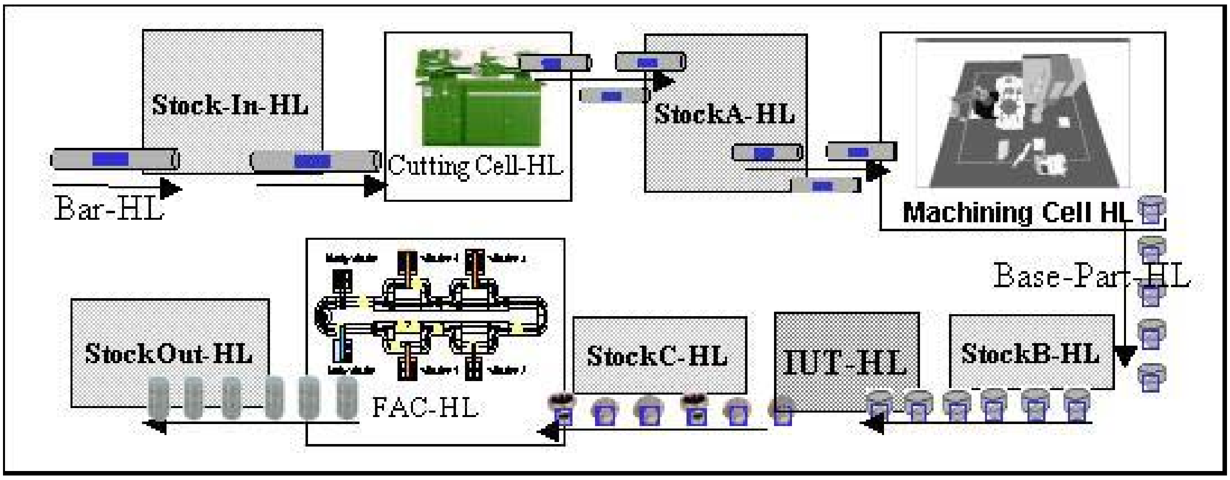

Figure 10 - AIPL context

In this context, there are two kinds of Rules: a new kind of Rules to decide good moments to create Smart-Product-HLs and Rules to allow those Smart-Products arrive in their production objectives. This entire scenario was simulated in ANALYTICE II using a holonic control based on the proposed meta-model. This H-MES had permitted simulate the production without previsions.

9. CONCLUSIONS

In this paper a conceptual solution for the product-driven Holonic Control or Holonic Manufacturing Execution System was proposed. Firstly, a holonification of resources is proposed, making computational homogenisation and giving some expertise to them, e.g. to express its capabilities/states and receive services requirements. This expertise allows Resource-HLs carry out a certain part of the control function, i.e. monitoring and command. After that, Rules are proposed to organise the co-operation between Resource-HLs, allowing process-driven HMES. For the Rules inference, a mechanism oriented to notifications was developed and used.

The article follows in the proposition of Smart-Product-HLs, regarding mass customisation issues. A Smart-Product-HL indirectly reserves Resource-HLs allocating an appropriate Rule. This Rule correctly co-ordinates Resource-HLs services to carry out the Smart-Product-HL desire. Therefore, a solution to product-driven HMES is found in these Smart-Product-HLs and Rule co-operations.

In this product-driven context, Rules are a decoupling mechanism between the negotiation of Smart-Product-HLs and Resource-HLs that allow organise and optimise those interactions. Still, Rules can be also used classically to take some conclusions, as the good moments to create the Smart-Product-HLs.

This generic architecture proposed has as first practical and direct contribution in the holonification of the simulation tool called ANALYTICE II. This robust and generic solution control facilitates the composition of the holonic systems in the ANALYTICE II. Some holonic control models, process-driven and product-driven, have been developed demonstrating the “meta” feature of the solution. As a result, the solution is considered a meta-model to HMES in HMS simulation environment.

The holonification of ANALYTICE II and the associated holonic control solution can be understood as a first step to compose real HMS and HMES, process or product-driven. The solution would have potential to real systems if Resource-HLs, like those simulated, could be really projected.

Over the mass-customisation point of view, this proposition and experiments had presented a tool to examine the product-driven benefits as a technological response. The results are in agreement with those presented by the IMS literature.

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