A viable system model for product-driven systems

Carlos Herrera, André Thomas, Sana Belmokhtar, Rémi Pannequin

International Conference
on Industrial Engineering and Systems Management
IESM'2011
May 25 - May 27
METZ - FRANCE

A Viable System Model for Product-Driven Systems ⋆

Carlos HERRERA [a], André THOMAS [a], Sana BELMOKHTAR [a], Rémi PANNEQUIN [a]

[a] *Centre de Recherche en Automatique de Nancy (CRAN), Nancy Université, CNRS Campus Science, Vandœuvre, France.*

Abstract

This paper describes a modeling approach for product-driven systems based on the Viable System Model (VSM). A general VSM description is presented, highlighting the pertinence of this approach for modeling intelligent product systems, specifically when a compromise between control and autonomy is aimed. An application is also provided for modeling a hybrid centralized/distributed production planning and control system. System modeling using the conceptual framework provided by VSM, allows to handle the complexity of the planning and control functions, considering aspects such as efficiency, flexibility, adaptability, scalability and reusability.

Key words: Product-Driven Systems, Viable System Model, Manufacturing Planning and Control Systems, Flexibility, Adaptability.

1 Introduction

The reduction of the Product Life Cycle caused by the ever growing demand for customization and global competitiveness, has imposed new challenges for many industrial sectors. These challenges force companies to organize and structure themselves, adapting their internal processes towards a high changeable environment and facing their own internal failures. In this context, centralized and hierarchical approaches applied to the decision making process, can be inadequate, especially under conditions of disruption and long-term changes [18,17]. An alternative approach to this conventional hierarchical organization is the concept of Product-Driven System (PDS).

A PDS, changes the vision to a more interoperable and intelligent system, postulating the customized product as the controller of manufacturing enterprise resources [23]. This leads to the design of an *intelligent product* [21], which has been defined as an entity with a physical and information-based representation, able to influence decisions which concern itself [19]. From a practical perspective, Radio-Frequency Identification (RFID) has been widely accepted as a suitable technology linking information systems with the physical world [33,29].

Despite the increasing development of PDS [24,8,9], currently, there is no specific modeling framework for this kind of systems. According to [22], an important condition for these new approaches is to contribute to the

⋆ This paper was not presented at any other revue. Corresponding author C. HERRERA.. Tel. +33 03 83 68 44 50. Fax +33 03 83 68 44 59.

Email addresses: Carlos.Herrera@cran.uhp-nancy.fr (Carlos HERRERA), Andre.Thomas@cran.uhp-nancy.fr (André THOMAS), Sana.Belmokhtar@cran.uhp-nancy.fr (Sana BELMOKHTAR), Remi.Pannequin@cran.uhp-nancy.fr (Rémi PANNEQUIN).

understanding of endogenous variables like emergence and self-organization, in a wide-plant automation context. In accordance with this, the appearance of these variables cannot happen if the system is not seen as a whole. Consequently, a key issue is to develop sufficiently general holistic frameworks for modeling these multi-agent organizations, integrating the decision making process at the different levels. In this way, the model should allow the system to exhibit proprieties such as: flexibility, interoperability, robustness, scalability, reconfigurability and reusability.

Therefore, the proposed modeling approach is based on the conceptual and theoretical framework proposed by the Viable System Model (VSM). This model, since its origin in the fifties, as the result of the work of Stafford Beer, has been subject of a continuous validation and application until now. Some recent related works applying VSM concepts can be found in domains such as: production management [16,27], autonomous distributed systems [14,26,30] or in modeling communities of autonomous agents [31]. This differs with the nonexistent utilization of VSM in the Intelligent Manufacturing Systems (IMS) approaches, considering its high similarities in terms of objectives and tackled problems.

The objective of this exploratory work is to describe the main concepts involved in VSM and how this model can be applied for modeling Product-Driven Systems. The high similarity in terms of objectives and topics, between VSM and the approaches arisen from the IMS initiative is also highlighted. As well, this paper presents an application to model a hybrid centralized/distributed Product-Driven Manufacturing Planning and Control System, focusing on how an intelligent product could be interpreted as a viable system.

This paper is organized as follows: section 2 presents a basic but sufficient description of the main concepts involved in VSM necessary to develop the proposed modeling approach. Section 3 presents the approach focusing on the elementary object of the proposed structure that is the intelligent product and also describes an application of VSM to model a Product-Driven Manufacturing Planning and Control System. In section 4 a discussion of the main findings and facts is presented. Finally, section 5 briefly presents the conclusion.

2 The Viable System Model

As previously introduced, the Viable System Model (VSM) results from the research work of Stafford Beer [3,4,2,7] in the domains of neurophysiology, cybernetics, operational research and social sciences. The origins of VSM date from the work of Beer applied to the steel industry in the fifties. This research can be placed in the line of works of Norbert Wiener, Warren McCulloch and Ross Ashby [12]. The main objective of the model was to identify and to explain *how systems are viable*, in other words, how it is possible that some systems can maintain an independent existence [7].

Although VSM is a general model for the study of any viable system, the most concerned application area has been *human activity organizations*, i.e., corporations, firms or governments [6,5]. In this domain, VSM changes the view of the traditional management model based on *command and control*, in which a control system is designed as a pyramid and such decisions are disaggregated in a top-down manner at different structural levels. The main difference, inspired by the biological organization, consists in changing this hierarchy by a *structural recursion.*

The premise of this change of perspective was inspired from the living beings composition (molecules, cells, etc...). Indeed, they have properties of autonomy, auto-organization and auto-regulation, allowing them an independent existence. The differentiation of their functions and the relationships between these elementary components produce more complex systems, without that subsystems essential properties would be lost. Also, one of the most important properties of a viable system is recursion. Any viable system contains and is contained by another viable system. Every subsystem maintains its autonomy towards its environment, but it also contributes to generate the viable system in which it is included. In that way, a viable system and its different subsystems have the same structural requirements. Consequently, a viable system supports its objectives thanks to an overall cohesion and adapts itself by the autonomy of its subsystems.

2.1 Viable system model functions

VSM was developed looking for *invariances* in organic systems. These invariances allow to define a homomorphism of their functions, organization and structure. Beer defines five elementary functions that any viable system must have: implementation, coordination, control, intelligence and policy.

Implementation : this function refers to *primary activities*, which produce products or services that materialize the identity of the system [11]. These activities add value to products and are identified after an analysis of *what the system does*. Besides, in a viable system primary activities can support a functional differentiation.

Coordination : this coordination function (anti-oscillatory) corresponds to the coordination among primary activities. In a viable system, this coordination is not necessarily accomplished in a top-down manner like a hierarchic management system. Indeed, primary activities can be coordinated in a centralized or distributed way thanks to cooperation and information exchanges.

Control : in a viable system, control refers to the function which regulates and ensures the auto-organization of the system. This is due to coordination and monitoring functions. Monitoring function (or sporadic audit function) allows at the same time to evaluate the actions of primary activities and to hold the coherence of the global activity (all primary activities). Notice that, control function is the function that defines the control/autonomy degree of the actions accomplished by the primary activities.

Intelligence : the intelligence function is responsible for system adaptability. This function is the link between primary activities and their environment. To achieve this adaptation, the intelligence function must be capable of treating the information which comes from the environment, with the objective to anticipate perturbations. Besides, this function is responsible of the coherence between local and overall system objectives.

Policy : the policy function keeps the system objectives at the different recursive levels.

2.2 Variety and recursion

The variety of a system is defined as all possible system states and it can be used as a complexity measure. In this way, a controller will be effective if it is capable of attaining at least the same number of states as those which it wants to control. This was expressed by Ashby [1] in the *law of requisite variety.*

"A controller has requisite variety - that is, has the capacity to maintain the outcomes of a situation within a target set of desirable states - if and only if it has the capacity to produce responses to all those disturbances that are likely to take the outcomes out of the target set".

To do that, a viable system tries to reduce the variety coming from the environment and to amplify the variety of its control function to reach a balance (homeostasis). The variety that system is not capable to control (residual variety), should be absorbed with the objective to ensure viability. Notice that if the system is not capable to control residual variety, it can lead to the loss of the systems identity.

Thus, control (management) is composed of three functions: policy, intelligence and control. The relationships between these functions show that the feedback between intelligence and control functions must take into account the objectives of the system at its recursion level. The coordination and monitoring functions correspond to the information flow which allow reduction and amplification of variety respectively. Furthermore, the viable system object of control, is the part of the system where primary activities will take place . This viable system can be decomposed in other viable systems at lower complexity levels. Figure 1 shows an example of a decomposition of a viable system in three subsystems. The property of recursion of VSM allows continuing this recursive process until the required level of detail. In the example presented in Figure 1, it is possible to break down each of the three viable systems in new viable sub-systems. Also, the whole system can be considered as a subsystem of another viable system at an upper recursive level.

Thus, for example, a football player can be seen like a viable system. In this case the respiratory or circulatory systems are viable subsystems of the whole "football player viable system". These viable subsystems can be then decomposed in other viable subsystems as the cardiovascular or lymphatic systems for the circulatory subsystem, and so on. On the other hand, the "football player viable system" can be also viewed as a subsystem belonging to a bigger viable system that could be the football team.

3 Product-driven systems based on VSM

3.1 An intelligent product as a viable system

As it was expressed before, a viable system is designed focusing attention on the primary activities, i.e., the system components which complete work tasks. A conventional recursive decomposition of a production system,

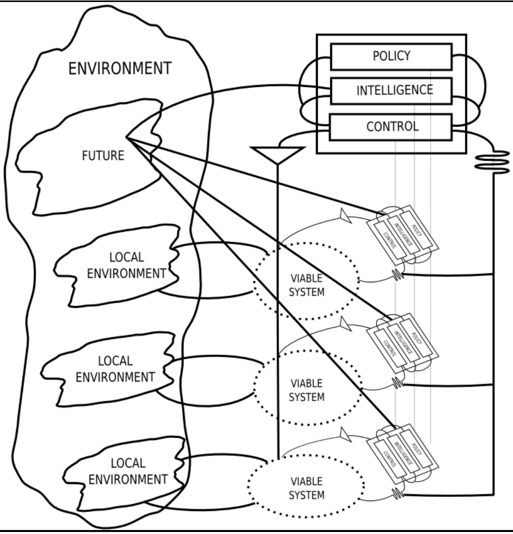

Fig. 1. The Viable Systems Model

will decompose the system, for example, on the shop-floor, production cells, production lines and machines [13]. In that case, machines would be the atomic entities of the system at the lowest recursion level.

In contrast with this conventional interpretation, we consider the product to be the elementary decision-making entity responsible for driving work tasks. Therefore, it is considered as the basic element of the production process and it is designed as a viable system. Others system entities such as machines, conveyors, automated guided vehicles, team workers, etc., are then considered in the environment. These entities interact with the product only in terms of events leading to lack of availability, disruptions, constraints, etc. Figure 2 shows the intelligent product structure which is proposed.

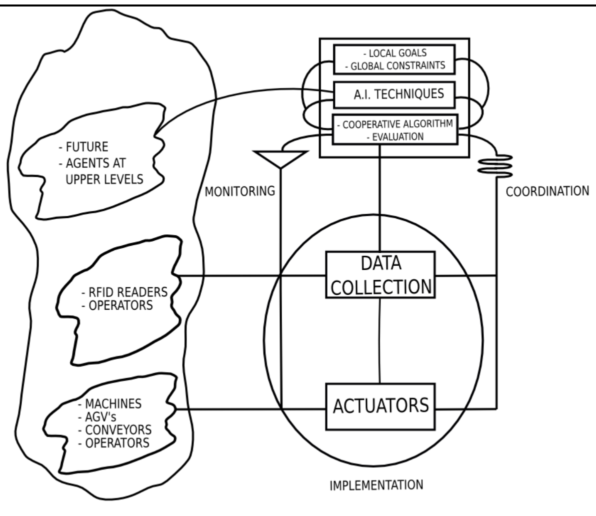

Fig. 2. The Intelligent Product as a Viable System

As it has been said in the introduction, the intelligent product is defined as an entity able of interacting and communicating with its environment. When this physical entity transits on the shop-floor, it will be able to recover information concerning both its own state and the system state. Then, focusing on the product, all the production planning system can be structured from the information recovered by this intelligent product. Also, decision-making problems are addressed to their corresponding aggregation level. This approach quite differs from the conventional holonic approach, in which products and resources are considered to be active entities [10]. The choice to not consider resources as belonging to decision-making entities, is voluntary made to express the central role played by the product in the decision that concern it. However, it is necessary to point out that VSM allows a multi-functionality of activities, like in living system.

The primary activities of the intelligent product are data collection and interaction functions. The data collection activity is designed as the action which allows the product to get information from other products and to give information to them. On the other hand, interaction functions allow products to interact with their environment, for example by using actuators. Table 1 describes the components of the intelligent product.

Table 1
Intelligent product components description.

Function	Description
Primary activities	Input/output data (data collection)
	Environment interaction activities (actuators)
Coordination	Communication between data collection and interaction activities.
Control	Internal activity regulation by coordination and monitoring.
	Auto-organization and evaluation
	Cooperative algorithm (interaction with others products)
Monitoring	Sporadic audit of the primary activities actions
Intelligence	Internal and external knowledge, future anticipation, response actions
Policy	Local goals and global constraints

Notice that product is designed with both, an informational and a physical part (as a holon). Then, at the different states of its life cycle, this product will activate these two parts according to its state in the system. Before beginning its manufacturing process this product has activated only its informational part (an active agent). Then, once it begins its manufacturing process, it should activate in addition to the informational part the physical one.

In this way, the product informational part will always be active. This informational part, *lives* in one or several computers, allowing it to communicate with others agents to make decisions in a cooperative way. An alternative is to load the informational part into the physical part, but its feasibility will depend on the characteristics of the manufacturing process. Notice that an intelligent product designed in this manner, belongs in the category of *cognitive agents*, rather than *reactive agents*.

3.2 Application for production planning and control

A Manufacturing Planning and Control System (MPCS) contains in general five main activities, these are Strategic Plan, Sales and Operation Planning (S&OP), Master Production Schedule (MPS), Scheduling and Execution. Each of these activities (plans), proposes decisions for different planning horizons. Commonly, decisions are taken using a rolling horizon, i.e., plans are recomputed with a certain frequency. In this way, strategic plan can be reviewed biannually or yearly, S&OP monthly, MPS every week, Scheduling daily and Execution in micro-periods of hours or minutes. Each of these activities makes decisions based at some level of product aggregation which can be product families, manufacturing orders, lots, finished products and components [32].

In this context, one of the main problems is to adjust decisions taken at the different levels. When internal or external disturbances occur, objectives at different levels are hardly fulfilled. Some of the most common disturbances are demand changes (external) and production capacity variations (commonly due to machine breakdowns). Then, frequent decision changes lead to a considerable system instability [15], which deteriorates both efficiency and productivity.

While at planning horizons of long and medium terms, changes are less frequent, in short- term horizons they are more recurrent which strongly degrade the system performance. In this context, a MPCS system must give enough flexibility at operational levels to allow adaptation to disturbances, but also, to ensure coherence with the objectives defined at the others levels.

Specifically, the proposed application tackles the problems of MPS and Lot Streaming. The MPS consists of defining the quantities to produce for each item (products), for a planning horizon (generally three or four months), considering weekly demand, costs and capacity of the system [25]. This problem is generally modeled like a capacitated lot-sizing problem (CLSP). Once quantities are obtained, these quantities must be subdivided into sub-lots, and also sequenced, to be launched in the different production stages, that corresponds to the Lot Streaming Problem [28]. In this way, it is possible to optimize the production flow reducing the weekly production makespan. Disturbances as changes of demand or machine breakdowns lead to the planning defined at the beginning of the week, already is no more valid, and consequently it is necessary to achieve adjustments towards the new conditions.

Therefore, the example application presented here, corresponds to a hybrid centralized/distributed system, which has for objective a self-adaptation face to internal and external disturbances. This system is based on a product holarchy, such that every decision level has a relationship with its product aggregation level. Regarding to the intelligent product introduced previously, the different levels are defined as *holon communities*, which have for objective to collaborate while assess and adapt decisions. The informational/physical nature of the system, added to the concept of structural recursion, lead quite naturally to the notion of holarchy. In a recent work [20], the author defines VSM as a holon organization. More precisely, this holonic organization is defined as a *cognitive holarchy* composed by sub-holons modeled such that viable systems. Then, we design this hybrid MPCS system such a cognitive holarchy modeled as a Viable System. This holarchy is composed of different product aggregation levels also modeled as viable systems.

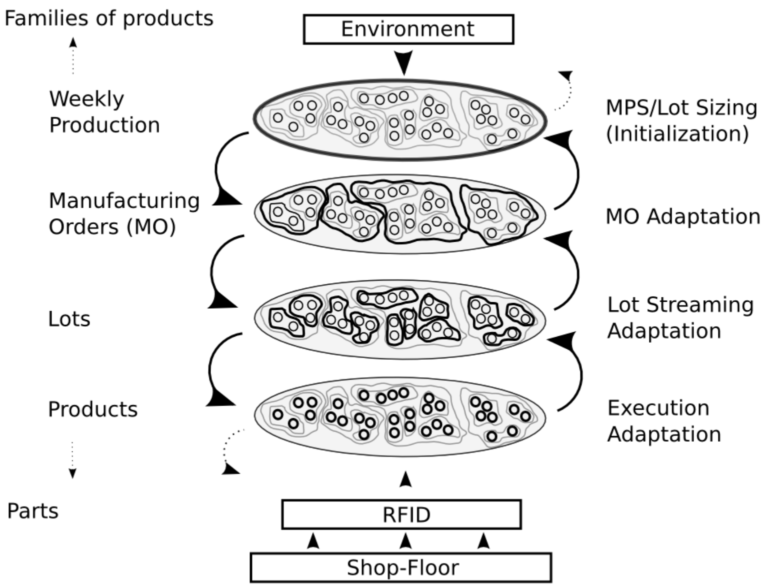

Fig. 3. Agent communities for planning and control

Figure 3 shows the different aggregation levels proposed. Therefore, at each level entities such products, lots, manufacturing orders and family, represent agents modeled as viable systems. All these levels are updated using the information provided by the lowest level (products). Notice that, at every aggregation level, it is possible to identify one or several decision-making problems. In this manner, control is based on the adaptation of decisions at each level.

The objective is to react to external variations (like demand changes), in a centralized way and in a decentralized way for internal perturbations (like capacity changes). For internal perturbations, if it is not possible to find an alternative solution at the corresponding level, the problem rises to the next upper level (bottom-up process) and so on. For external perturbations, central system modifies global targets causing an adjustment (top-down) of lower-level decisions and defining new realizable targets at each level. While bottom-up adaptation process (right side in figure 3) has a cooperative character, top-down adjustment process (left side in figure 3) have a mandatory nature.

Figure 4 shows the viable system model of the hybrid MPCS system proposed. Notice first, that the higher level deals with the family product corresponding to the classical S&OP decision level. This suggest that the approach allows to consider all product families or upper product aggregation levels also.

Figure 4 presents all the components of the proposed hybrid system. Product holons (1) have the structure presented in figure 2, and are presented here as black points. In the same way, all recursive levels have the same structure, and for each one, all management functions must be viewed as control, intelligence and policy functions. At the upper level, the environment allows to obtain demand forecast, cost, and also, constraints arising from market and norms. An interesting point is the link with the Customer Relationship Management (CRM) activities of the company. (22) shows that manufacturing order agents can eventually recover information from the environment. In this application, product agents update their information by a RFID system (23).

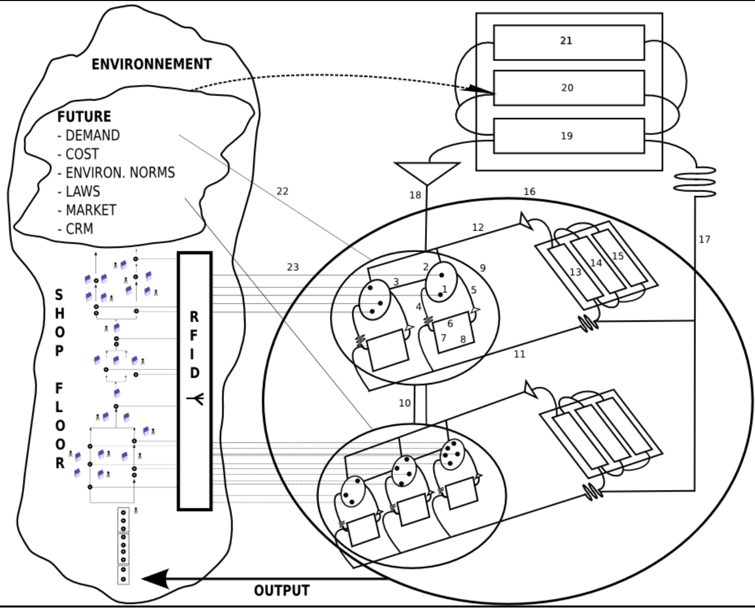

Fig. 4. The hybrid MPCS system

As said before, the proposed system is composed of four recursion levels, product, lot, manufacturing order and family. The whole decision system (MPCS) will be elaborated by the sum of all control, intelligence and policy functions relatives to all levels. Notice that, the combinatorial nature of the decision-making problems and the variability of the parameters (demand, capacity, etc.) do not allow an on-line re-computation of the plans once perturbations arrive. To cope with this weakness, the centralized decision about manufacturing orders quantities (lot sizing problem), is computed with a parametric approach. This method provides a set of alternative solutions according to the chosen parameters [15]. Tables 1,2,3 and 4 describe briefly the functions at each level.

Table 2
Product level description

Level	Component	Description
Product	1	The physical part of this component, dispatch information relative to its state and the state of the system using RFID technology. The relationship between physical and informational parts (agent) of the product is one-to-many. Also, the physical part of the product agent evaluates and decides to cut or to continue production of a lot once perturbations level exceeds a threshold.

Table 3
Lot level description

Level	Component	Description
Lot	2	A lot agent is composed of a variable quantity of product agents. Lot agents cooperate to adjust size and sequence changes induced by product agents.
	3	It corresponds to the information flow between lot agents.
	4	The coordination function at this level refers to the communication protocol among product agents.
	5	This function updates lot production time from product on-line data.
	6	The control function implements a distributed algorithm to exchange products with others lot agents.
	7	The intelligence function evaluates adaptation changes.
	8	Policy function at this level ensures minimal and maximum sub-lot sizes, manufacturing order quantity and number of available lots.

4 Discussion

The relationship between hierarchy and heterarchy has been widely studied by VSM. In fact, VSM cope with this in terms of degree of control/autonomy implemented in all control functions. The monitoring function is

Table 4
Manufacturing order level description

Level	Component	Description
Manufacturing Order	9	These agents guide a local search procedure to find near optimal symmetric solutions using parametric information provided by the central level.
	10	It corresponds to the information flow between manufacturing orders agents.
	11	The coordination informs about search results.
	12	The monitoring function at this level can trigger a replanning of weekly production quantities.
	13	Local search function computes near optimal feasible solutions (plans) according to parametric alternatives and the system state.
	14	The intelligence function maintains updated the information about real production time of each manufacturing order.
	15	The policy function provides information about current manufacturing order quantities.

Table 5
Weekly production level description

Level	Component	Description
System	16	This agent represents the higher component level including all the other levels. Specifically, this agent represents all activities implemented by the proposed application.
	17	In this particular application, this level is implemented in centralized way. Then, the coordination informs changes of each manufacturing order quantity.
	18	This function updates manufacturing order quantities information.
	19	Control function at this level has three sub-functions: evaluation, PMPS and lot streaming. (a) Evaluation function assesses the global performance of the system in terms of efficiency, stability and feasibility. (b) The PMPS function (Parametric Master Production Schedule) gives alternatives of quantities to produce for the period. To do that, a parametric lot-sizing model gives several solutions considering the trade-off between cost and instability according to the production capacity variation. This function is modeled as a Parametric Mixed Integer Programming (MIP) model, computed off-line once information about the next period has been validated.c) Lot streaming function computes a lot streaming MIP model to obtain initial values for lots and its sequence.
	20	The intelligence function uses forecasts to estimate parameters like demand or cost. Demand can also be adjusted considering Customer Relationship Management (CRM) functions, including changes and proposals.
	21	The policy function keeps the system performance in terms of costs and stability.

expressly defined with the intention of auditing the functioning of primary activities (agents) and not to control as in conventional system of command and control.

Another concern in the origins of VSM has been adaptability. As it was described in the previous section, VSM was developed with the objective to understand the mechanisms which allow biological organisms to survive to changes in the environment. A viable system is designed to self-adaptation in a changing environment, by the implementation of the necessary mechanisms to support its viability. Here, it is not possible to identify a specific function which ensures adaptability, since the whole system is defined to fulfill this objective, thanks to its different elementary functions. This characteristic of adaptability is also one of the main objectives of the paradigms arising from IMS initiative.

Moreover, one of the basic properties of the viable systems is scalability because these systems are structurally recursive. This notion of recursion has been mainly exploited by bionics manufacturing systems, which make an analogy from biological organisms. These are composed of atoms, molecules, cells, membranes, organs, systems and finally organisms. This notion has been also exploited by fractal manufacturing systems which show clear properties of recursion and auto-similarity. The last property of auto-similarity of fractal systems is also included in the viable systems through its property of structural recursion. In that way, a viable system will keep the same structural requirements at any complexity level. These concepts have a direct relationship with reusability, which is another objective of IMS systems. These three points about autonomy, adaptability and scalability highlight the strong relationship between IMS approaches and VSM objectives.

On the other hand, an important shortcoming of conventional centralized/distributed approaches, i.e., MPCS systems using MRP II based planning system and lean manufacturing techniques (kanban method) to production control, concern the lack of flexibility in the decision making process. According to APICS, flexibility can be defined as the ability of the manufacturing system to respond quickly, in terms of range and time, to external or internal changes. Flexibility can be reached, to absorb disturbances and ensure feasibility of plans, introducing some involvement of operators in the decision process. Since decisions could not wait until recomputing, decentralized (local) decisions are usually taken without any guarantee of global performance. Consequently, the predictive planning is used as a reference planning where deviations happen frequently. Several possibilities could be adopted, although only few of them will be able to maintain an acceptable global cost. In this context a system such the one proposed, can be useful maintaining a coherence with the global objectives and give the needed flexibility at the operational level.

Finally a hybrid centralized/distributed manufacturing control system can be seen like a viable system if the designers of such systems are able to ensure recursive characteristics. That is to say that each decision level include the lower ones. To be realistic this kind of concept induces real time closed loop systems. This last point could be seen as a limitation according to the available currently technology. But the last improvements made in the field of Auto-ID technologies lead us to think that we will be probably able to implement such systems soon.

5 Conclusion

In this paper, we have presented the main concepts involved in the VSM. Also, it has been possible to identify several common points between IMS approaches and VSM objectives. Moreover, we have presented an application of the proposed modeling framework to model a MPCS product-driven system. The main advantage of this application is to reach a coherence among the different decision levels giving a high degree of flexibility to the system. The proposed modeling approach and product-driven systems can be adapted to be used in different industrial applications.

Acknowledgments

The authors gratefully acknowledge the financial support of the CPER 2007-2013 Structuration du Pôle de Compétitivité Fibres Grand'Est (Competitiveness Fibre Cluster), through local (Conseil Général des Vosges), regional (Région Lorraine), national (DRRT and FNADT) and European (FEDER) funds.

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