Distributed Manufacturing Enterprise Modeling: the DME framework, towards an ontological approach

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Abstract. The context of our research is the distribution of manufacturing systems associated with the emergence of new types of organization (Virtual or Extended Enterprise, Holonic Manufacturing Systems, D-CIM...) which tend to distribute activities, competence, responsibilities and decision making capacities of the enterprise on units having a high level of autonomy. The study of these types of organization lead us to propose and define the DME (Distributed Manufacturing Enterprise), a conceptual framework for a knowledge based modeling of distributed manufacturing systems. Then, we present the principal behavioral and descriptive knowledge reference sets which participate to an ontological definition of the DME. Finally, we conclude on perspectives concerning the elaboration of a formal modeling framework of the distributed manufacturing systems.

Key Words. Manufacturing Systems, Enterprise Modeling, Distribution, Cooperation, Autonomous Units.

1. Introduction

In this end of the 90s, manufacturing enterprises are increasingly faced with a global market and a customer centered production. This situation leads to a demand of products of greater quality, available in minimal lead times, less expensive and personalized [1][2]. To reply to these demands, enterprises adopt new types of organization allowing them to increase their flexibility and their reactivity, as the extended enterprise, the virtual enterprise, the concurrent engineering, Holonic Manufacturing Systems, and finally the D-CIM (Distributed-CIM).

Our research concerns the modeling of distributed manufacturing systems by explicitly taking into account the knowledge and leading to the definition of ontologies. In this paper, we develop first of all the context of our research linked to the transition of manufacturing systems of the 80s to distributed manufacturing systems, associated with the emergence of new types of organization. The study of these new types of organization leads us to propose and define the DME conceptual framework (Distributed Manufacturing Enterprise) for a knowledge based modeling of distributed manufacturing systems. Then, we present principal behavioral and descriptive ontological knowledge reference sets, participating to an ontological definition of the DME. Finally, we conclude on perspectives of our research concerning the elaboration of a formal modeling framework using ontologies based on these knowledge reference sets.
2. Emergence of the distributed manufacturing systems

2.1. The present production context

The current production context is very different from the one of the 80s and justifies the emergence of distributed manufacturing systems. The market development requires an evolution of manufacturing systems which can be called a systemic rationalization process [2][3]. This rationalization process concerns an increase of the performance by the implementation of specific industrial strategies. A good illustration is given by the transformations of the Aerospatiale company [4] in which the increase of the performance is organized around three main industrial strategies: (i) the installation of a subcontracting policy; (ii) the technological specialization and (iii) the focus on specific jobs.

In the organization, these industrial strategies result in transformations of organizational and technical nature. These transformations deeply affect the physical, decision and information systems of the organization. They exploit to the maximum the new information technologies into procedures, interactions, communication and control mechanisms of the organizational structures. In the case of Aerospatiale, the industrial strategy implementation has led to transformations such as: (i) the complete overhaul of the management system (henceforth based on management of interfaces between subcontractors); (ii) the harmonization, the homogenization of data, and (iii) a new organization of the enterprise characterized, among others, by more autonomy of the units.

In general, the systemic rationalization process currently applied to the manufacturing systems tends to privilege: (i) a pull flow rhythm of production; (ii) the research of an organizational flexibility and (iii) a focus on basic jobs and correspondingly the development of subcontracting networks.

2.2. On the necessity of a conceptual framework

Associated to this rationalization process, new industrial organization types have been proposed. Among the most significant are: (i) extended enterprise [4], (ii) virtual enterprise [5], (iii) holonic manufacturing systems [6] and (iv) D-CIM (Distributed-CIM)[7]. These new industrial organization types which we associate with the distributed manufacturing systems, present many similarities, emphasizing particularly on two fundamental points: (i) the distribution of competence (know-how), responsibilities and decision making capacities of the enterprise leading to the characterization of autonomous units and (ii) the development of cooperation policies (coordination and collaboration) between these units.

We associate these new industrial organization types with the emergence of distributed manufacturing systems. The modeling of such systems has necessary to consider these two fondamentals points. In this modeling, we looked at the CIMOSA architecture (Computer Integrated Manufacturing - Open System Architecture)[8] which seems to us the most advanced proposal in manufacturing enterprise modeling and more particularly in the modeling framework proposed. As we have already developed by detail in [9] we propose to extend this framework to better take into account the two fundamental points previously evoked. The first main adaptation that we propose concerns the capacity to express cognitive aspects necessary to assign more autonomy and decision making capacities to active units. Indeed, the FBS paradigm (Function-Behavior-Structure) of the functional view represents and manipulates constructs through the object concept from the software engineering. This concept seems us badly adapted to the knowledge representation. The second adaptation we propose have to permit to this framework to better take into account distribution and cooperation notions between active units composing the system of production (in CIMOSA the notion of distribution is only taken into
account through the concept on integrated database). Others more technical adaptations can be also proposed : (i) the adaptation of the expression of the behavioral models currently based on a too rigid event driven structure conferring thus a deterministic behavior forbidding the consideration of events non definite a priori, then (ii) the transaction notion defining the relationship between the units expresses which seems us too rigid and limited semantics and badly adapted to modeling the cooperation. 

In conclusion, with some adaptations, the CIMOSA modeling framework should be relevant for modeling distributed manufacturing systems. Such adaptations concern necessarily the ability to take into account the distribution of competence (know-how), of responsibilities and of decision making capacities on autonomous units of the manufacturing enterprise and the development of cooperation policies (coordination and collaboration) between these autonomous units. Currently, few works of research have yet been developed on these points and our contribution is an effort to approach them by defining a conceptual framework adapted to the modeling of the distributed manufacturing systems that we have called : DME for Distributed Manufacturing Enterprise.

3. The DME Conceptual Framework

The definition of the DME conceptual framework is necessarily based on central notions of distribution. This notion is not sufficiently clearly defined in the area of the industrial engineering, therefore, we suggest to try to better understand it first.

3.1. Distribution in manufacturing systems

By inspiring ourselves of the derivation principle of CIMOSA, we consider first of all the manufacturing enterprise with two distinct abstraction levels (see figure 1) :

- the requirements level that concerns the requirements in decisions and information necessary for the realization of activities of the enterprise. This level can be formulated as a set of n activities grouped according to their membership to the great functions of the enterprise, for example : sales activities, production activities, purchasing activities, etc. To each activity, noted A_i, we associate a triplet (f_i, d_i, i_i) to show that decisions d_i and information i_i are necessary and sufficient to realize the function f_i associated with the activity A_i.

- the operational level concerns the realization of activities A_i defined to the previous level. More precisely, after specific organizational choices this level defines a set of active entities called unit, which with the R_i resources realize f_i functions associated with A_i activities. At this level each unit, noted U_i, is associated to a triplet (P_i, D_i, I_i) where I_i represents information and D_i represents decisions which are available at the U_i unit level used to realize the P_i process, which consists of the implementation of functions f_i associated with activities A_i. Note that D_i and I_i are not necessarily sufficient to realize P_i. Each R_i resource represents the real material means (a manufacturing machine, brute matters, etc.) or more abstract means (a software, a program of a numerical machine, etc.) of the enterprise. Resources are shared between units according to their needs to realize their process P_i. Finally, U_i unit and R_i resources are joined according to a specific organizational structure that allocates resources to units and associates units to each other.
The change from the requirements level to the operational level is made through organizational choices (see figure 1). These choices consist of defining units and distributing on these units information and decisions making processes. In these organizational choices we distinguish the three following distribution types:

- the functional distribution that concerns the distribution of competence and know-how of the enterprise, precisely the allocation of $P_i$ process to unit $U_i$;
- the decisional distribution that focuses on the distribution of the management activities of the enterprise, in other words it concerns the allocation of decision making processes $D_i$ to unit $U_i$;
- the informational distribution that concerns the distribution of information stocking, processing and communication means of the enterprise, in other words the choice of the information $I_i$ affected to unit $U_i$. This distribution constitutes the support for the realization of the two other distributions.

These different organizational choices do not impose that characteristics $(P, D, I)$ of $U_i$ units correspond inevitably to characteristics $(f, d, i)$ of the $A_i$ activities that are associated to them.

### 3.2. Definition of the DME conceptual framework

The DME conceptual framework for the modeling and the study of distributed manufacturing systems is based on a set of basic definitions concerning units.

First of all we define a unit $U_i$ as an active entity able to be endowed with intelligence and autonomy, and capable to cooperate with its kind by means of resources, to accomplish activities $A_i$. The intelligence of such a unit is defined as an organized set of knowledge and mechanisms of reasoning allowing it to make decisions in order to carry out common and individual actions. A unit $U_i$ is autonomous if it has informational means $I_i$ and decisional means $D_i$ that contribute to the realization of the process $P_i$. The unit $U_i$ is as autonomous as its means are important and totally autonomous if these means are sufficient to realize $P_i$. Note that this definition characterizes the autonomy as a relative property: a unit is considered as autonomous if it has decisional and informational means allowing it to be committed in the realization of a process but without these means being sufficient for the realization of the process. The realization of the process can for example necessitate a collaboration with other units.

The cooperation can be defined as a form of intelligent interaction implementing methods of coordination (planning, negotiation, etc.) in order that activities performed by autonomous units permit the achievement of the enterprises objectives. The cooperation is performed thanks to knowledge and appropriated
reasoning mechanisms and can be justified by: (i) the achievement of activities cannot be realized by only one autonomous unit, either by lack of competence ($P_i$), or by lack of information ($I_i$), or by lack of decision capacity ($D_i$), the cooperation permits here to give to autonomous units, either the possibility to exchange information and decisions in order to fill the lack, or to join them to obtain a sufficing set of competence to realize activities of the enterprise; (ii) the lack of availability of the autonomous unit, consequence of commitments already fixed to realize other activities, the cooperation permits to find compromises (substitute the unit non available by another unit, or to wait the release of the unavailable unit, or to revoke commitments rendering the unit available); and finally (iii) the incapacity of the autonomous unit to realize an activity because a resource is unavailable. In this case, the cooperation permits to optimize the resources utilization.

We define the distribution as a relative property of an organization (distributed manufacturing system). The distribution depends on the proportion of characterized autonomous units to the operational level. Thus an enterprise will be distributed if it is endowed with a subset of autonomous units. The bigger this subset is and the more autonomous its units are, the more distributed the enterprise will be.

4. Towards an ontological approach of the DME

The notion of ontology is largely used in the knowledge representation area [10], but also in the enterprise modeling and the enterprise integration areas [11]. If one of the main roles of the ontologies is to facilitate the sharing and the reusing of knowledge, there is no truly consensual definition of what is an ontology. Thus, for some [12], it designates the metamodel that describes the structure on a basis on knowledge, a theory fixing what entities can exist in the comprehension that a cognitive agent has its own universe. For others, more pragmatic, [13] and in a knowledge sharing perspective between agents, an ontology is a specification that clarifies a conceptualization, it describes existing concepts and relationships between these concepts for an agent or an agents community. Finally, an ontology can be a sort of dictionary guaranteeing a communication on the knowledge level between agents, a formal description of entity and their properties designating objects of an area and being able to permits to define a terminology shared between agents adhering to it. It is this last definition that we adopted to model the DME.

To construct such an ontology associated to the DME framework, we have identified different reference sets of knowledge (defined a priori) that describe specific aspects that contribute to define it. We distinguish two kinds of reference sets of knowledge: the behavioral reference sets and descriptive reference sets.

4.1. The behavioral knowledge reference sets of the DME

The behavioral reference set associated to the DME depend on the behavior notion defined by examination of interactions between autonomous units.

4.1.1. The reference set Action: action taxonomy of the DME

This reference set has as objective to permit the study of the DME behavior. It consist of listing the different acts realized by autonomous units that modify the DME environment. To that purpose, we distinguish three great action types.

Physical actions use shared resources that compose the DME. They can be classified in [14]: (i) preparatory actions provide to autonomous units the necessary means to begin sequences of actions (generation of programs for machines with numerical command, the set-up of the machines); (ii) morphological actions or transformation of matter (a product $P$ will become after a processing a product $P'$); (iii) quantitative actions (the assembly of $N$ products $P_1...P_n$ gives a
product of type P); (iv) qualitative actions or control (test of products or machines); (v) transportation actions insure the circulation of products within the DME; and finally (vi) stocking actions allow to store intermediate or finished products.

Actions of communication allow the information transfer between the different autonomous units. They do not modify directly the environment of the DME but they can influence it. We distinguish two type of actions [15]: (i) actions "to make a demand" realized by autonomous units to request the intervention of others units for the realization of physical or decisional actions; and (ii) actions "to receive a demand" realized by autonomous units at the reception of demands of its fellow requesting the realization of physical or decisional actions.

Actions of decision performed by the autonomous unit for the decision-making and that often need the realization of other actions. These actions can be performed in four types of situation: (i) normal situations; (ii) abnormal situations a priori defined (concern foreseeable risks); (iii) abnormal situations not a priori defined (concern unpredictable risks) and finally (iv) situations of preparation and attribution of tasks to units. We distinguish two types of decisional actions [16]:

- reflex decisional actions do not need elaborate reasonings and are often empirical. They use expertise based on the experience of production operators. These actions are performed (i) in normal situations implementing mechanisms of coordination that guide the autonomous unit intervention to perform activities of DME, and (ii) in abnormal situations implementing emergency mechanisms to return to a normal situation.

- reasoned decisional actions need elaborate reasonings and concern: (i) abnormal situations not a priori defined implementing reasoning mechanisms to return to a normal situation, and (ii) the preparation of tasks to be executed by autonomous units with the help of cooperation mechanisms. These actions are often performed when reflex decisional actions are incapable to cope with disruptions.

4.1.2. The reference set Coop: cooperation in DME

This behavioral reference set defining the cooperation, noted Coop, is based on a classification of methods of coordination associated to the type of interaction used by autonomous units. The cooperation is studied here in reference to research works in Distributed Artificial Intelligence (DAI). These works seems sufficiently generic to be applied to numerous areas including that of the industrial engineering. We distinguish three categories of interactions (cooperation, antagonism and indifference) observable according to: (i) the nature of the activities (compatible or incompatible); (ii) the access to the resources (sufficient or insufficient) and (iii) competence of the units (sufficient or insufficient) [17] (see Table 1).

<table>
<thead>
<tr>
<th>Activities (A)</th>
<th>Resources (R)</th>
<th>Competencies (P)</th>
<th>Types de situation</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatible</td>
<td>Sufficient</td>
<td>Sufficient</td>
<td>Independence</td>
<td>Indifference</td>
</tr>
<tr>
<td>Compatible</td>
<td>Sufficient</td>
<td>Insufficient</td>
<td>Simple collaboration</td>
<td>Cooperation</td>
</tr>
<tr>
<td>Compatible</td>
<td>Insufficient</td>
<td>Sufficient</td>
<td>Traffic jam</td>
<td>Cooperation</td>
</tr>
<tr>
<td>Incompatible</td>
<td>Sufficient</td>
<td>Sufficient</td>
<td>Collaboration coordinated</td>
<td>Cooperation</td>
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<tr>
<td>Incompatible</td>
<td>Sufficient</td>
<td>Insufficient</td>
<td>Collective competition</td>
<td>Antagonism</td>
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<td>Incompatible</td>
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<td>Sufficient</td>
<td>Individuals conflicts for resources</td>
<td>Antagonism</td>
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<td>Incompatible</td>
<td>Insufficient</td>
<td>Insufficient</td>
<td>Collectives conflicts for resources</td>
<td>Antagonism</td>
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</table>

Table 1 - Categories of interactions [17].

The various interactions between autonomous units composing the DME can be charaterized as (i) in relation to activities A that are here necessarily compatible; (ii) in relation to R resources is considered as either insufficient or sufficient, they
are then been either inexhaustible or always available (quite rare in industrial engineering); finally (iii), in relation to competence \( \text{P}_i \) of units that can be insufficient for the complete realization an given activity. Correspondingly, the main methods of cooperation associated to the DME are typical cooperation by coordinate collaboration (see table 1) and allow autonomous units to coordinate their actions and share their competencies.

4.2. The descriptive knowledge reference sets of the DME

The descriptive reference sets concern intrinsic properties of the main concepts defining the DME.

4.2.1. The reference set Chain : the value chain of the DME

Demands of production come from the sales sector of the enterprise and define values chains, represented by the descriptive reference set Chain. According to [4] we define a values chain as a set of interdependent activities, allowing to identify main activities in design, production, marketing, distribution, recovery, etc. The content of a chain of values can be considered as being a plan of production (orderly activity sequence of production) for the realization of tasks that have to be executed by autonomous units. Autonomous units translate this plan in solicitations for the realization of physical actions.

The rhythm of pull-flow driven production leads to a product centered production and to minimal stocks. Autonomous units perform demands of production by cooperation. The generation and the maintenance of value chains are realized by classic PCP systems, which receive in entry production demands (quantities, ranges of manufacture, etc.) that have to be executed by the production system according to a planning strategy with different time horizons. In a first step, they realize a planning for long and average term (forecast scheduling) to generate the initial value chain. In a second step, if disruptions occur, they realize a planning for short term (reactive scheduling) to straighten the situation.

4.2.2. The reference set Unit : the autonomous unit of the DME

As we have already seen, each autonomous unit is characterized by a triplet \((P, D, I)\). The descriptive reference set "Unit" characterizes the autonomous unit with this triplet and the definition of three essential subsystems.

The physical system \((SPhy)\) stemming of the functional distribution is linked to the component \(P\) of the triplet. Its finality is the realization of activities required by the values chain at unit level and concerning physical actions mobilizing abilities.

The decision system \((SDec)\) stemming from the decisional distribution is linked to the \(D\) component of the triplet. Its finality is the coordination of physical actions of the autonomous unit realized by the \(SPhy\). It realizes reflex and reasoned decisional actions to insure this coordination as well as the cooperation with others units that may be required.

The information system \((SInf)\) is the result of the informational distribution and it concerns the component \(I\) of the triplet. Its finality is to integrate, to support the other systems \((SPhy\ and \ SDec)\). We distinguish several levels of integration : (i) integration within the autonomous unit by stocking and transferring information manipulated by the \(SPhy\) and the \(SDec\); (ii) integration of the autonomous unit with shared resources used during physical actions; in this case, the \(SInf\) allows autonomous units to "perceive" resources shared according to their specific needs, and finally (iii) integration of an autonomous unit with its kind allowing all cooperation by the realization of actions of communication between units.

4.2.3. The reference set Res : the shared resources of the DME

The descriptive reference set "Res" characterizes the shared resource \(R_i\) of the
DME. As in the resource view of CIMOSA, all resource is assimilated to a structured set of information and its utilization to an update of its information. This update is strictly on the responsibility of the autonomous units. Resources being shared, they are submitted to a control of availability (occupation of the resource at one time). This control depends on the SDec of the autonomous units (not necessarily on those that use theses resources).

4.2.4. The reference set StrOrg: the organizational structure of the DME

The descriptive reference set "StrOrg" determines the organizational structure of the DME. This structure can be constituted from three entities: (i) the specialized centers that concern gatherings of autonomous units and shared resources according to their competence, for example flexible manufacture workshops, a cell of manufacture, etc.; (ii) the subcontractors that are often associated to small and middle size specialized enterprises to which of activities considered as secondary are transferred; (iii) the groups that are associated to opportunist gatherings of autonomous units, constituted for the realization of common activities, for technological or economic interest. They can also be formed by other groups and can bring together specialized centers and subcontractors.

The relationship between these three entities are specified in the behavioral reference set "Coop" already introduced. The reference set "StrOrg" allows to define the classes of organization according to affected roles to autonomous units and existing relationships between these roles, thus:

- if the autonomous unit's autonomy is weak, the interaction between autonomous units will be constrained by an organizational structure of the hierarchical type resting on a set of relationships of subordination between roles played by autonomous units;
- if the autonomous unit's autonomy is important, on the contrary, interactions are less constrained and we are in the presence of an heterarchical organizational structure. Autonomous units maintain dynamic reports between they aiming to establish a group synergism to safeguard objectives of the enterprise. At a given time, the set of these relations characterizes the organizational structure of the enterprise.

We have already defined the autonomy as a relative property of the autonomous units (they are "more or less" autonomous). In consequence, the organizational structure is between these two extreme structures that are the hierarchy and the heterarchy. It is characterized by sets of autonomous units maintaining relationships of equality (characteristic of the heterarchic structure), with some units that can assume the role of co-ordinators (characteristic of the hierarchical structure). Sets of autonomous units can thus be organized between them.

5. Conclusion and perspectives

The new industrial organization types which we associate to the distributed production systems, present many similarities, emphasizing particularly on the distribution of competence (know-how), responsibilities and decision making capacities of the enterprise leading to the characterization of external or internal autonomous units and the development of cooperation policies (coordination and collaboration) between these units. The study of these types of organization lead us to propose a conceptual framework for the modeling of distributed manufacturing systems called DME for Distributed Manufacturing Enterprise. To define this conceptual framework, after having attempted to better understand some fundamental notions such as distribution and autonomous in a production context, we have identified principal behavioral and descriptive knowledge reference sets,
defined a priori and independent of any application, which participate to an ontological definition of the DME.

Now, our research concerns the definition of an operational modeling framework of distributed manufacturing systems. We develop this research in the context of the architecture GERAM [18] proposed by the IFAC/IFIP task force on Architecture for Enterprise Integration. We work currently on the definition of specification languages allowing to formalize and to use the ontologies elaborated from the knowledge reference sets that we have proposed in this paper. Such formal languages combine a logical approach (predicate logic of the first and second order) with a multiagent systems approach for their capacity to apprehend notions such as distribution, cooperation, coordination, negotiation and their capacity of execute and/or simulate models allowing their validation. A first attempt, AOP3S (Agent Oriented Programming Paradigm for Production Systems) [19] has already been realized from the work that we have presented in his paper.

6. References


