CONTROL OF MANUFACTURING SYSTEM BY AGENTS OF MATERALS, PARTS AND PRODUCTS

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Abstract

This paper deals with a new multi-agent approach to control a manufacturing process system where agents represent materials, parts and products, thus allowing increased reactivity and flexibility. It is based on bionic manufacturing paradigm, where raw materials carry information about possible processing. The Manufacturing System (MS) is made up of a set of autonomous and intelligent agents as in a society. The simulation of the control system, of discrete-event type, is based on agents of materials and products. An experimental platform was built for this purpose. An agent, able to negotiate operations that the product must undergo on the stations in manufacturing, is attached to it. This agent has all the necessary information on production environment, objectives, constraints and rules. A Product Model (PM) for production based on a social approach with a decentralized architecture is presented. The PM was introduced into a common experimental platform developed by the partners of the SPACS Project. The latter integrates all the elements necessary for the management of the production in interaction with the Electronic Data Interchanges (EDI) amongst clients and subcontractors.

Keywords: Flexible Manufacturing Systems, Product Model, Scheduling algorithm, Multi-agent System.

Presenting Author's biography

Peter MITROUCHEV graduated from Technical University of Sofia, Bulgaria in 1983, Degree M.Sc. in Mechanical Engineering. He obtained his Ph.D. degree in Automation and Computer Sciences from the University of Besançon, France in 1992. Since September 1993 he has been working as Associate Professor at Grenoble University "Joseph Fourier-1" in the Department on Mechanical Engineering. Performing research at the Laboratory G-SCOP. Member of the European network of excellence VRL-KCiP. The research area addressed covers: Modeling and design of mechanisms and multi-body systems, Assembly Disassembly simulation, Digital mock-up, Self-scheduling for flexible manufacturing systems and Mechatronics.

1 Introduction

1.1 Bionic manufacturing paradigm

Industrial manufacturing started with Taylorian manufacturing paradigm about one century ago. At that time, nature of manufacturing processes was understood to be deterministic. Processes were designed to last and to produce huge quantities of products of the same type.

New manufacturing paradigms emerged within last twenty years: holonic [1], fractal factory [2], complex manufacturing systems [3] and bionic paradigm [4].

These paradigms address and solve challenges of modern production that needs to be flexible, distributed, adaptive, lean, cost and quality effective, and environment friendly.

Presented work builds on principles of bionic manufacturing paradigm [5].

The paradigm looks into Nature and builds from the principles that can be discovered while studying survival techniques, evolution principles and bio-physical-chemical foundations of life. While these work for Nature, they have potential to work for humankind activities, especially in highly organized and structured activities, i.e., in manufacturing.

Bionic paradigm looks into Nature on a scale from individual cells to ecosystems. The mechanisms, that were discovered, while studying life on earth, were distilled and reused for bionic control architectures in manufacturing [6]. On a bio-cellular level, it is about throughput of substances and energy. It is enzymes within cells, and hormones outside cells, that control the throughput of substances and energy through cell boundaries. In a manufacturing cell, it is about throughput of material and energy. Control decisions are performed on an intra- and inter-cell level.

Biological cells build tissues, organs and bodies. Manufacturing cells are base for build-up of production floors, factories and enterprises.

Basic entity in bionic manufacturing is modelon [7]. It has mechanisms for production, for decision-making process and for communication with other modelons. A modelon can consist of other modelons and it can be a port of a modelon – same as about objects in object oriented programming, which is most familiar matter to attendees of EuroSim07.

Modelon structure is used to describe part-system, entity-whole relations, interaction and cooperation of building blocks and self-reflected responsibilities. Structuring systems into modelons and relations among them gives means to model, understand and design complex hierarchies of decision-making processes for control.

One example of an implementation of a bionic distributed control system consists of machines and Automated Guided Vehicles (AGVs). The example is proposed and annotated on a theoretical level only in [5]. Modelons of parts in production, and modelons of machines and AGVs correlate their activities for success of a whole, which is optimized production.

1.2 Manufacturing practices

In static scheduling, it is assumed that the number of jobs, their processing sequence and the respective processing time are a priori known. However, in real time situation there are many uncertainties associated with part arrival, processing time and machine availability [8, 9]. Mean tardiness, maximum tardiness and the number of tardy jobs objectives were used to evaluate the performance of each dispatching rule but minimization of flow time based and tardiness based performance were not proposed. In most of studies, it is assumed that machines in the shop are continuously available [10, 11, and 12]. However, in a nabufacturing system are risks of machine breakdown, for example, quite frequent.

In this context, we consider that traditional scheduling approaches, using combinatory optimization, are inefficient because they fail to take into account the dynamic aspects, which are prevalent [13, 14]. The disturbances (i.e.,. machine breakdowns, quality problems, organizational problems, modifications made by the commercial department and others) lead to a difference between the real state of the shop floor and the prearranged schedule [15, 16]. The complex prearranged schedule has to be re-computed and the next solution may be very different. Hence, optimization must not deal with a hypothetical balanced state but rather with the dynamic state of the system.

Therefore, an enhanced organization amongst prediction, anticipation and reaction is required. Prediction concerns medium and long term scheduling, whereas anticipation concerns short term scheduling. Anticipation allows successive operations to be linked in time.

The aim of this paper is to demonstrate that anticipation on a very short term allows a near real time scheduling to be built, based on the events of the shop floor. We developed an approach named "*Product approach*", based on a social model in which the *resources* and the *products* are both active to schedule the operations [13, 14]. The suitable solution emerges from the negotiation of the operations between products and resources for a very short-term period.

In this context, we took part in Synchronous Production Amongst Clients and Subcontractors (SPACS) project, subsidized by the Rhône-Alpes regional council. Its goal was to propose a global solution for manufacturing control, aiming at the integration of the production system with the whole of the company functions. The starting points of our work are already existing developments of a multi-agent model of production ensuring short-term synchronization amongst clients and subcontractors [17, 18, 19, 20, and 21]. Our work, within the SPACS project, was more particularly related to a) *integration of the functions of design and manufacturing*, being articulated as a "Product Model", b) to the subject of this paper (control of manufacturing system by agents of parts in production).

The results of this study may be useful to product designers and to production-system designers enabling them: a) to establish a model, which is appropriate for the piloting of the production system, and b) to have all the information for the manufacturing of the product.

This paper is organized as follows. General presentation of the SPACS Project is presented in section 2. The objectives of the research within the framework of SPACS Project are presented in section 3. Thereafter, section 4 describes the simulation, reasoning, the results of the simulation and their validation. The introduction of the product approach for scheduling and control of manufacturing systems is addressed in section 5. Section 6 describes the product as a control actor in a flexible manufacturing system. The following section 7 presents the simulations, the results and their validation. Finally, discussions and conclusions are given in Section 8.

2 General presentation of SPACS project

Within the SPACS project, an approach of production running management by the product was developed (cf. §.4). Its goal was to propose a more global solution:

- by making a total analysis of the constraints and advantages shared by client and subcontractor,

- by studying the problem of scheduling, and having a scheduling scenario in a very short term (for the subcontractor),

- by suitably articulating the control of manufacturing with Electronic Data Interchanges (EDI) between clients and subcontractors,

- by suitably articulating exchanges of information allowing each partner to anticipate the work orders.

Thus, the project aimed at developing approaches and a methodological support adapted to the short-term scheduling of the production of Small and Middle Enterprises (SME) sub-contractors, in good synchronization with the customer or partner companies. The impacts at the organizational, economic and operational level of the installation of these approaches were also estimated [20].

2.1 Contribution of the participants

The *Economic Institute of Research Production Development* (EIRPD, Grenoble) contributed on the economic aspects, competencies and contractual relations. It was also the coordinator of the project. The *G-SCOP* Laboratory, Grenoble approached to the development of multi-actors, autonomy, and coherence aspects, the convergence of the decisions and the actions of each partner as well as the Produced Model (PM).

The *Laboratory of Automatics of Grenoble* (LAG) contributed to the modeling and to the evolution of the distributed methods of scheduling. The *Laboratory of Software for Computer-Integrated Manufacturing* (LSCIM, Annecy), contributed to the management aspects, to processes for installation of new methods and studied consequences on the levels of the hierarchies. The *Laboratory of Industrial Automatics* (LIA, Lyons) studied and evaluated the safety of the production flows of products. It also approached the provisioning in conformity of quality and date.

Renault Industrial Vehicles (RIV) (purchased thereafter by Volvo) has a strong experience in coordination with a great number of "Rhône-Alpes" Area subcontractors, in the field of manufacturing production. It also expressed its economic and industrial interest for the improvement of this coordination.

2.2 Economic multi-companies context of the project

The industrial partners who took part in the project were representative of the Undercutting Industry of the *Vallée de l'Arve* (74, Haute Savoie). The Valley of Arve is one of the most industrialized valleys of the French Alps. Approximately 70 % of the activities of the French undercutting industry are located there. These companies represent 14000 jobs. Set up on 40 km^2 they are specialized in manufacturing of batches of various mechanical components in significant volumes. The companies associated with the project were:

- PERNAT 74 Scionzier, important volume of production with RIV. With a work force of 150 people, on the sites of Marnaz (3000 m^2) and Scionzier (2400 m^2), its sales turnover is 16 M€ with a catalogue of 1700 references of parts.

- BRIFFAZ 47 Marnaz, company of "Mechanics and Undercutting", RIV's first supplier of undercutting.

- EUROTEC-MANDUCHER specialized in the field of plasturgy.

- RIV, Renault Industrial Vehicles.

3 Objective of research within the framework of SPACS project

The scientific goal of the project was to propose methods of synchronization, which do not introduce artificial constraints into the organization and into the local production management. The goal consisted of:

- preservation of autonomy of the partners to the most extent,

- proposition of architecture for decentralized decision-making process,

- ensuring of independence of small partners, in order to effectively manage their resources, and to protect them against risks within their local systems.

In such a decentralized context, it is necessary to have synchronization mechanisms based directly on the production targets, such as defined by the supply agreement with the customer.

3.1 Consequences

Consequently, relationships amongst client and subcontractor change. The credibility of a subcontractor does not only depend on the quality of the products and the strict respect of the deadlines. It also depends on its capacity of reaction to the inevitable dysfunctions occurring during the manufacturing. Thus, we needed:

- a reliable support of communication in order to exchange information necessary to reactivate production management (cf. § 3.2),

- a dysfunctions' model in order to anticipate on their propagated effects (cf. § 7.1).

The margin of autonomy is essential to locally absorb the risks resulting from manufacturing processes or caused by the fluctuations of orders. The profitability of the companies, able to answer the constraints of a synchronous production, involves adequate contractual conditions that are difficult to define.

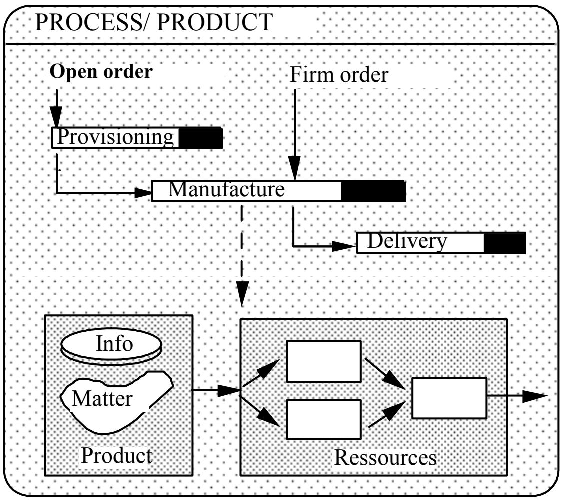


Fig. 1 General representation of relations between clients and subcontractors

Thus, the production system becomes *reactive*, characterized by a *synchronous approach*, rather than *interactive*, characterized by an *asynchronous* approach.

3.2 State of Industrial art. Supply agreements

Let us recall the traditional approaches of prescriptive type [21] where:

- products are inert,

- operators are slaves,

- all depends on the person in charge of the planning.

Open (estimated) and firm orders were generated via Electronic Data Interchanges (EDI) [16]. The EDI is a teleprocessing application allowing, according to a standardized format, exchange of computerized documents amongst the computers of partners (commercial or others). Then it allows integration of these documents, once received, validated and accepted, into the computer of the recipient and their possible immediate processing. That allowed us:

- to split the quantities to be delivered (a delivery per day for example),

- to make firm these quantities only at the last moment (a few days, even a few hours).

Among the adopted solutions, we note:

- it is better to use open (estimated) orders and EDI in order to reduce losses of time and error margins,

- producing with *in just* by integrating the client delivery orders into the production schedule of subcontractor (a margin may be required),

- reducing this margin, without risk of rupture of provisioning for the customer, it was proposed to soften the supply agreement,

- in certain cases giving the subcontractors the possibility not to provide the requested quantities, in the express condition that they warn the customer early enough.

We proposed to open the supply agreement towards a subcontractor or groups of subcontractors who are not subjected to the same risks at the same time.

3.3 Problematic and reasoning

The suggested model is based on the running of the production by the product and on a model of society [20]. As we said, the product is considered as an actor. Whereas for the traditional approaches of prescriptive type the products are inert, the operators are slaves and all goes up with the responsibility for planning, our approach is based on a model of society in which:

- the products choose their operators, (autonomy of the actors),

- the products and the operators make an appointment, (production guided by the product), All the actors of this society collaborate with the same aim, to satisfy objectives laid down by the production plan. The decisions are made in coordination with all the concerned actors. Each one acts at the same time at the estimated level in the short run (appointment) and at the reactive level (reassignment of the appointments in the case of disturbances). That supposes coherence and a continuity of the whole activities of Design-Management-Production in close relation with the Integrated Design, without forgetting the determining role of the human, being in the capacity as an intelligent actor, factor of autonomy.

The implemented mechanism is based on rules of good direction used in client/subcontractor relations with service providers working on return. These rules are distributed in an identical way on each actor and are applied in parallel and in real time.

4 Simulation, reasoning, results and validation

Among the industrial partners associated to the project, the companies of the undercutting sector played a particular role, because they were intended to be used as models for the construction of a platform on which simulations would be carried out. Thus, the model presented in this study was tested on a platform representing a company of undercutting, supplier for the car industry Renault Industrial Vehicles (RIV).

The collection of necessary data required a long-time presence of researchers on the factory's site. The first analysis carried out *in situ* allowed collecting a precise description of material flows among the various activities of parts production. It also allowed a careful reflection on the significance of the synchronous production and its implications in term of production management. Then, the analysis could be widened by means of the regular participation of a researcher in the installation of new software for production control PRODSTAR [21] on the site of a partners' company.

The software allowed the commercial management, the management of the purchases, the management of technical data, quality and production control to be taken into account. Initially the level of production management was limited to a level of planning of "reactive oriented product method" (ROPM) type. Then, a database of the technological platform was constituted, to which the model presented above was applied. The validation of the suggested concepts was performed through the simulation that is presented below.

4.1 Evolution. Safety and flows simulation

After planning optimization, we proposed an evaluation of the flows safety compared to the capacities of the subcontractors according to three stages.

- model for total planning,

- simulation of flows and multicriteria assistance for results' interpretation,

- Data-processing support.

Flows simulation presupposes that random dysfunctions and decisions are taken according to criteria, which measure simultaneously safety and delays, compared to planning. The goal was to provide subcontractors with rules of scheduling which give satisfactory performances in term of safety and productivity.

An interaction modeling with the partners by stochastic processes was adopted. It is the case of:

- the arrival of EDI from the client,

- the delivery of subcontractors,

- the delivery of possible suppliers.

Simulation consisted in replacing a system by a logico–mathematical model [22]. Then this model was translated into a program, able to generate data characteristic of the system. Finally, that data (average value, confidence intervals...) was interpreted statistically in order to draw some inferences from it. The adopted approach for simulation was the *approach by process*. Various software were tested (WITNESS, Simfactory, ARENA,) in order to retain the one which would be the most adapted to represent the problem in accessible form for the subcontractors. The software was also supposed to have a sufficient data-processing opening in order to articulate a level of managing, required by each of our various approaches of synchronization. This choice seemed very important to us because beyond the validation of the concepts, subcontractors could use the simulation as a decision-making aid. Finally, the ARENA/SIMAN software was retained allowing:

- the system's structure description: the processes are described by predefined functional blocks (size of a resource, transport of a part, machines, transport systems, storage...),

- the description of entities, which represent orders, parts or information: the algorithm of change of state is known in a block. The block can call upon a bookshop of preset procedures or upon a procedure user, who describes the decision rules,

- the definition of the running rules which make it possible to lead the entities in the system: the activities are launched by the passage of entities in the functional blocks; the system's state is characterized by aggregate variables and attributes carried by the entities.

This software, having a graphic animation, also allows the visualization of the evolution of the system's state (circulation of the parts in the workshops, activities of the machines, composition of stocks). At any moment of the simulation, it was possible to obtain information on the state of an object (machine, entity...) and to carry out statistical analyses. The production process of the Pernat Company partner was studied as an example. Fig. 2 below summarizes it.

Let us remember that the simulation of a system with discrete events provides performances' measurements of the system. In this study of a MS (Pernat subcontractor enterprise), we were more particularly interested in the following performances:

position of the delivery date compared to the interval planning,

safety of the production process.

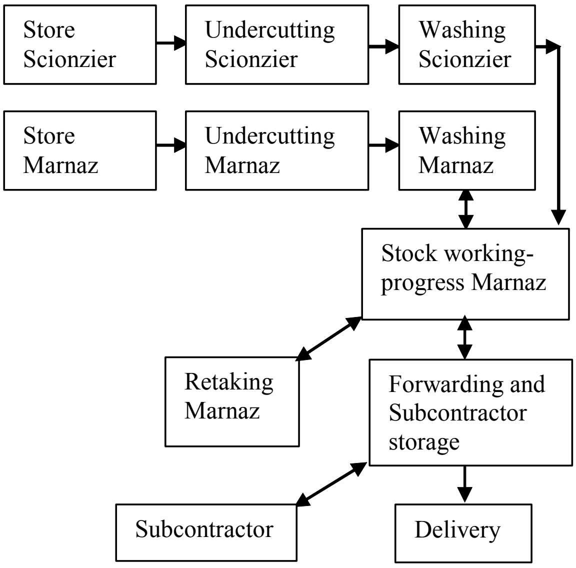


Fig. 2 Flows' simulation and evolution

The simulation provided a confidence interval for each one of these performances. To compare two control strategies, one is often confronted with a problem of multicriterion decision. However, a decision generally implies several criteria, which can be qualitative or quantitative. This is a complex process, which required the implementation of a methodology. The object of the decision was initially delimited, and then all the alternatives were given. Then the criteria were determined and a part of them aggregated. Lastly, a procedure, which allows the best possible solutions to be chosen according to considered criteria, was sought. Let us note that to determine the final solution, a human intervention is sometimes necessary.

Quantitative criteria were chosen in this study. Such a criterion is a function of set of alternatives towards a completely ordered set. The criterion of performance was the position compared to the interval generated by planning. The criterion relating to safety was then defined. The procedure of selection thereafter was sought and adopted. Let us recall that there exist three main approaches for procedure selection:

- aggregation in a single criterion,

- outclassing (on classification),

- interactive interactions.

Among these possibilities, the third one was adopted.

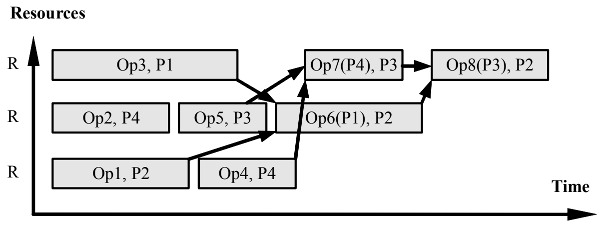
Thereafter, we took interest in the definition of the "measurement" of performance related to *safety of flows* between the clients and sub-contractors. This *safety* is the criterion, which was taken into account in the process of decision-making aid, in addition of the position of the delivery dates compared to the intervals of planning. This criterion was finally included in the simulation model.

4.2 Information exchange and activities' synchronization

The Laboratory of Software for Computer-Integrated Manufacturing (LSCIM) developed an interface organizing the exchanges of information and synchronizations of activities called PROPILOT [20]. Firstly, the simulation made possible to reproduce the operation of the undercutting company, then to apply the models of piloting in order to estimate their effectiveness. This analysis required to define several criteria of quantitative and qualitative evaluation (delay of a part, level of stock, cost…). It was thereafter possible to analyze the received requests by the subcontractor in order to evaluate its limits and over costs generated by the rush orders and by a lack of anticipation on the client's part.

5 Introduction of the product approach for scheduling and control of manufacturing systems

The product concept corresponds to the parts produced by the shop floor and may represent an elementary component, an assembly of several elementary components or a set of similar components. The operation concept corresponds to all the transformation, handling, transportation or assembly operations of the products. The resources are human operators and machines that perform the operations.



This chart represents a process of preparation and assembly of a product with 4 components, using 3 resources. Assembly operations aggregate a product component with a single resulting product.

Fig. 3 Example of Gantt chart

The aim of the scheduling is to assign in time the operations to the resources.

5.1 Scope of research of the solutions

To define the scope of research of the solutions, let us consider:

- the set **P** of the products and their components,

- the set **R** of the resources with their tools,

- the set **T** representing the times.

The operations can be formally defined as an element of the **PRT** set which is a Cartesian product of 3 sets: **"PRT = P x R x T"**. The scheduling consists in finding, for each product, an oriented graph in PRT, where each node of the graph represents the exclusive meeting between a resource and a product or its components, for some time, to perform an operation. For an assembly operation, the product groups several components together: this product may already have had other operations and therefore the graph has a tree structure (Figure 4, below).

Gray rectangles represent the operations.

Duration of an operation is represented by the height of the rectangle.

Each operation takes place at a meeting among a product, its components, if any, and a resource.

The operations chain according to the sequence of elaboration on the product.

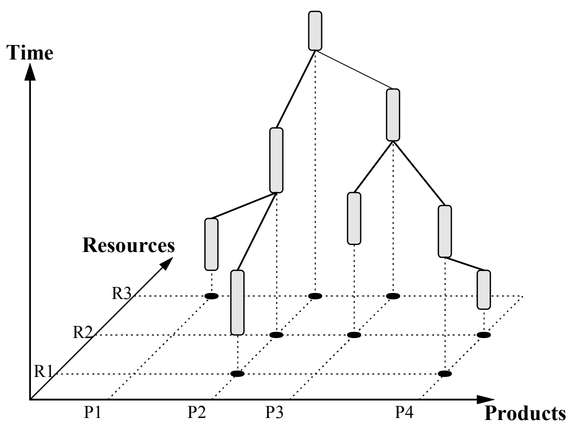


Fig. 4 Space of solutions

5.2 Classical approaches

The problem of manufacturing control is normally approached by the means of the planning and the scheduling. The problem is posed in terms of production flow and of resource allocation. The outcome of these steps is classically Gantt chart (cf. Fig. 3), that freezes the operations allocated to each resource, in amounts of allocated time.

Thus, resources can be "theoretically" used to their full extent. Therefore, the resource «should be» used optimally. This approach can be said to be based on manufacturing operations and is characterized by the answer to three questions that are, in order: "Who - When - What":

Who does the operation? The answer is on the Resources axis of the diagram.

When does the operation take place? The answer is on the Time axis of the diagram.

What or which product is concerned by the operation? The answer is found in rectangles representing the operations on the diagram.

In fact, the priority is given to the second question and time is privileged because the operating cycle of a product depends on whether it is used properly. It seems to be natural to give priority to the time when we try to synchronize the production (i.e. we try to find a coincidence between the beginning of an operation and the end of the previous operation). However, this coincidence is difficult to obtain simultaneously for the resources that should never be idle and for the products that should never wait in an intermediary stock.

Furthermore, this diagram masks many degrees of freedom**, which** could confront disturbances. Besides, the increase in the quantitative and qualitative variety of products causes more and more disturbances. To respect the prearranged scheduling, margins between operations, important batch groups and security stocks are used. These solutions are in opposition with a maximal use of resources and decrease of stocks. To avoid these solutions the Gantt chart is called into question, but not the reasoning: operations grouping on several levels are performed to reduce the impacts of unexpected events [23]. Operation and resource switching are forgone to allow a real time decision.

6 The product as a control actor in a Flexible Manufacturing System (FMS)

Let us remember that in the *classical approach* the problem of manufacturing control is normally approached by the means of the planning and the scheduling. The problem is posed in terms of production flow and of resource allocation. The outcome of these steps is classically a Gantt chart that freezes the operations allocated to each resource, as a function of time. This approach can be said to be based on manufacturing operations and is characterized by the answer to three questions that are, in order: "*Who* does the operation? – *When* does the operation take place? – *What* or *which* product is concerned by the operation? [24].

The *product approach*, proposed here, aims at higher flexibility and reactivity. It is based on a *society model* where the members are *products* and *resources*. This approach leads to rearranging the order of the questions: What? Who? When? The product becomes

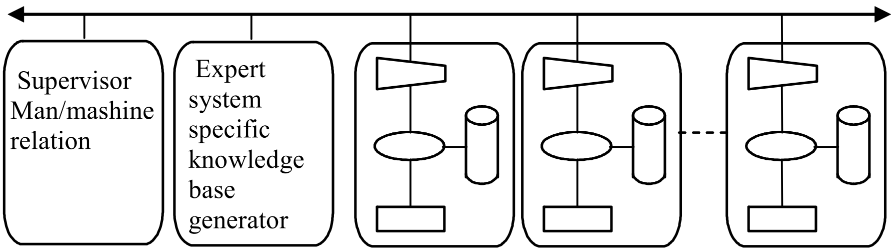


Fig. 5. General architecture of the Product-Oriented Approach

an active element of the production system and takes part in the decisions-making process which defines its' further production. Each product communicates and negotiates with all the resources to make appointments for each operation. The products are like customers and the resources are service providers: thus, the production system is made up of a set of autonomous and intelligent agents able to cooperate to achieve the global goal of the whole system.

The fundamental principle of product approach leads to associating all the knowledge and all the decision capacity required for the production control. Thus, the product possesses the specific knowledge to search for and treat the information on the production process: production goals, decision rules, equipment features and production environment [19]. This specific knowledge base contains all information on the product, including:

– its identity, its functional and structural features, its parameters,

– the process and the operational sequence to produce the product,

– the priority weights,

– the equipment features and production environment.

It also contains the information on the prearranged schedule, the up-to-the-time state of advancement and quality of performed operations, production goals and decision rules**.** This information or knowledge is used to find out a heuristic solution to achieve the planned objectives, taking into account the unexpected events. The resources are autonomous, too. They have a specific knowledge base containing the required information to perform operations.

Two special entities are introduced to complete this structure.

- The first entity specializes in *supervision* and man/machine relationships. It acts when human decision is essential. Thanks to this entity, overall safety of the system is increased because the human operator is always informed and associated with the quantitative decisions.

- The second special entity is an *expert system*, which gives to each product all the initial information, and the specific knowledge-base required to schedule and to control the system.

The behavior of these two entities depends on the global environment, the global production goals and events occurring. They form the link between the planning level, which defines the manufacturing objectives, and the control of the system [19]. Their global knowledge insures global consistency and vertical integration of production data.

The global resulting architecture of the system is shown in Fig. 5 below (cf. also § 6.1).

To establish a link with the CODECO approach (COordinated DEcentralized COntrol) [9], these specialized entities represent the coordination level. However, they do not interfere with the decision process and each execution entity is completely autonomous. The function of the specialized entity is to prepare the production context and the decision framework to allow harmonized behavior of the global manufacturing system.

6.1 Architecture of the product-oriented approach

The proposed *product approach* is characterized by the decentralization of the control. The control is based on a set of autonomous, homogenous and cooperative entities. In some previous researches, we developed a completely decentralized control approach [17, 25] in which each "execution entity" controls an element (or resource) of the operative system. These execution entities are completed by specialized entities for man/machine relationship and supervision. The new step in this approach is to consider that products are execution entities. Thus, products become actors of the manufacturing system.

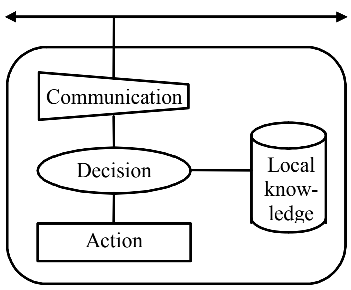


Fig. 6 Organization of the decentralized control

The fundamental principle of control decentralization relies on the homogeneous set of elements taking and executing decisions at the same time. These elements are autonomous, cooperative and coordinated by their goals. We consider each element of the system as an autonomous entity (cf. Fig. 6). Each entity has a local knowledge base and ability of "Communication", "Decision" and "Action".

- *Action* represents the ability to control the physical part of the process. An action corresponds to an elementary operation of the process.

- The *decision* part gives the ability to coordinate the actions of an entity with the other entities and to face unexpected events.

- The *communication* part creates the link for cooperation and information exchange between entities.

Thus, each entity is an *actor* of the control, able to realize depending tasks in co-operation with other actors. It is clear that all the levels of the classical hierarchy of Control must be present inside each *actor* of the operating part [18].

This decentralized approach simplifies control of the MS. It attaches a particular importance to events that involve actions [18]. The autonomy gives to each module the ability to locally eliminate disturbances and, consequently, the system reacts as close as possible to the place where events occur [16]. Furthermore, with this approach, architecture of the control system allows a complete integration of all the control levels, into a homogeneous, modular and open structure.

6.2 Self-scheduling and control, driven by the product

As we said, each product is considered as a *service caller* or a *client*. The product is able to communicate and to negotiate with the other autonomous entities, resources or servers, in order to find out the best schedule. In this way, the products are able not only to organize and control the system but also to control the machines. Each product keeps an *agenda* in which it records the operations to carry out. For each operation the identity of the server, the start and end dates are recorded. The resources are also autonomous and are able to accept or to refuse the client's requests. They also have an agenda. In order to avoid the combinatory explosion and to reduce the computing time, the product searches for the best end of the operation time for two or three consecutive operations. In the disruption case, autonomous entities react rapidly and locally. To this end, appointments with the stopped machine are cancelled and the products try to find another machine.

The product takes the initiative for negotiating the appointment because it has the information on its operation sequence and their approximate duration, its due date and its operation progress. It also knows the suitable resources for each operation. The negotiation protocol is the following:

1. For the first operation to carry out, the product communicates with all the suitable resources and makes a provisional appointment. A beginning date and an end date are negotiated. The product takes into account the transportation time and the resource takes into account its potential setup-time.

2. For the next operation, if there are still operations for the product, it communicates with all the suitable resources and makes provisional appointments. Thus, the product obtains one or more appointment sequences for two consecutive operations. It could communicate and make provisional appointments for the next remaining operations.

3. Then, the product chooses the best sequence of operations and communicates with all the machines to confirm the chosen appointments and to cancel the others.

If a breakdown occurs, the autonomous entities react locally and rapidly: the appointments with a stopped machine are cancelled and the product tries to find another machine [26].

If a conflict for an appointment request occurs, the product with the highest priority makes its appointment before the other. Many usual decision rules may be used such as: FIFO (First In First Out), LIFO (Last In, First Out), SPT (Shortest Processing Time), EDD (Earliest Due Date), MOR (Most Operation Remaining), FOR (Fewest Operation Remaining), etc.

6.3 Quality of solutions and functions of supervision

Each product and each resource aim at satisfying its' own criteria. The quality of the global solution (in terms of productivity) depends on the proper succession of all the operations for all the products on all the resources of the manufacturing system. Products and resources do not take into account the global state of the system and only solve local problems. However, the presented negotiation protocol allows consecutive operations to be linked to find favorable sequences, to limit the waiting time for the products, the idle time for the resources, the transport time and the setup-time.

A near *just-in-time* behavior with a steady flow of the production is expected, though it cannot be absolutely demonstrated (in the current state of our work and other known work). Effectively, with the appointment mechanism and with the use of priority rules, each product is programmed to progress as fast as possible and each resource is to sequence operations with a minimum lost time.

7 Simulation and results

This approach has been validated with the SMECI software. SMECI is a program environment for development of knowledge-based systems in various fields such as design, simulation, complex diagnostics and planning. In SMECI environment, all entities (products or machines) have been represented in form of objects that possess the necessary information for communication, negotiation and decision. Using this interface, it is possible to implement our approach and to have real time simulation of a Flexible Manufacturing System (FMS) functioning [14]. We modeled the prototype of an FMS, which is shown in Figure 7 below. This system consists of:

– an automated storage and retrieval system (AS/RS),

– a storekeeper robot (R1),

– three process robots (R2-R4),

– four belt conveyors (a conveyor for each robot),

- a central conveyor.

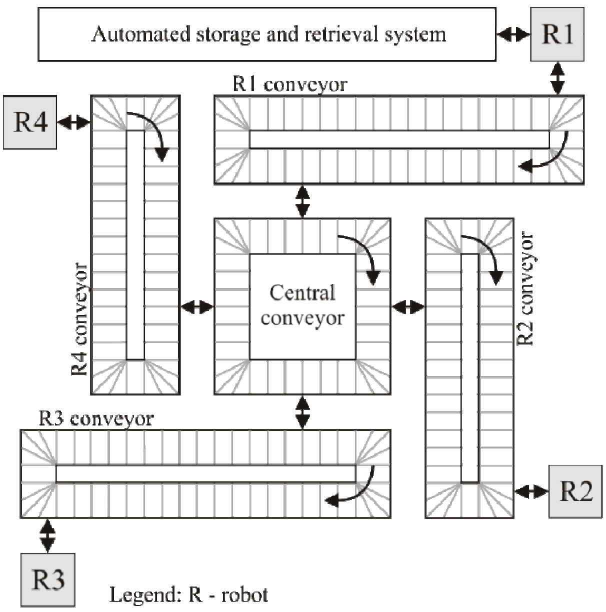


Fig. 7 Structure of the FMS

The assumptions are that:

– the robots are able to carry out six different operations with a specific tool, operations have a different setup time and a different processing time,

– the operation process is made up of no more than six different operations, but one operation can be repeated several times,

– the priority weight of each item in production depends on its due-date and on estimated duration of the remaining operations. The priority weight is gradually increasing as more time passes from the last operation.

7.1 Conflict problem and coordination mechanism

To avoid communication conflicts amongst products and machines, only one communication token is used for all the products that are present on the conveyor. In this way, at any one time, only one product can communicate with machines and request appointments. This is not a problem because the required time to make an appointment is very short. If two or more products need the token simultaneously, the product with the smallest ratio of available time over the priority weight will obtain it.

The coordination mechanism resembles the appointment mechanism described in § 4.1. When a product tries to find a machine for assigning one of its operations, it communicates with all the suitable machines. The products have all the required information to compute the transport time from one machine to another. The resources have all the required information to find out the set-up time and the duration of operations. Furthermore, each resource and each product has an agenda (appointment book). These agendas represent the negotiated appointments amongst products and resources, the operations to carry out, the beginning and ending times... The interactive procedure between a product and resources is organized in four steps:

- The product requests the earliest available date for each machine and the expected duration for this operation. It checks if it is possible to reach the machine before this date and propose a provisional appointment.

- Considering the first step results, if the product has outstanding operations, the product communicates again to request appointment for the next operation.

- The product keeps the solution, which gives the best end time for the second operation (or for the first operation if it is the last).

- It communicates once again to confirm the chosen appointments for the two consecutive operations. If the product has a high level of priority, it immediately makes another sequence of appointments.

Afterwards, the product goes to the appointments to carry out its operations. The appointment mechanism begins again when its last operation ends, in order to take into account the effective end time of this operation.

7.2 Disruption case. Simulation results

When a breakdown is detected for a machine, its appointments that have not been carried out are not valid and the products that were assigned to this machine have to find another machine. We choose to cancel all next appointments with all the machines and to restart the appointment procedure. This proposal is motivated by two main raisons:

- each product keeps a position corresponding to its priority rank,

- the number of products on the conveyor is limited and the communication times are very short compared with the operation time. When the failure is set all the appointments are cancelled and the appointment procedure begins again.

In the first simulation, we assumed that:

- there is no breakdown in the production system, and the priority weight is the same for each product,

- the machines are able to carry out several operations and an operation can be carried out on several machines,

- the conveyor capacity is unlimited.

Simulation results show that the:

- average machine utilization time for this system is eighty seven percent,

- average processing time for an item in production is forty-nine percent. Average waiting time for an item is forty-three percent. The rest of the time, eight percent on average, is spent in transport.

- decrease in number of products being simultaneously present on the conveyor results in a decrease of the waiting time.

- reduction in the number of operations that each machine can perform, results in increased waiting time and in decreased transport time.

The results show also, that:

- a reduction in the number of operations that each machine can carry out entails an increase in the waiting time and a decrease in the transport times.

- that the increase in the priority weight does not change the global results.

Generally, in this first situation, the machine's utilization rate is always more than eighty-six percent.

In the second situation, breakdown constraints were imposed. On average, the machine utilization rate, the transport time and the waiting time do increase. In general, a very good rate of occupation for the machines (almost identical to the first case) has been obtained but the rate of transport time has increased by thirty percent. The best conditions for self-scheduling are observed in the case where duration of the operations is quite conform. Thus, it is interesting, if possible, to group short operations in one operation and to subdivide the long operations.

8 Conclusion

In this paper, a *Product Model (PM) for manufacturing* has been presented. It was implanted in a common experimental platform developed by all the partners of SPACS Project. The PM integrates all the necessary elements to the piloting of the production in interaction with the EDI (Electronic Data Interchanges) amongst clients and subcontractors. The platform is also essential to direct the steps of research towards the difficulties encountered by the machine operators. It is also the support of demonstration and validation of the methods and tools under development.

However, optimized operation requires a good balance between the load and the capacity of the workshop. This is obtained by spreading the fabrication orders to avoid waves in the workshop and jams at the entrance. Therefore, thanks to the autonomy of product entities and resource entities, our model allows an immediate reactivity of the system. Meanwhile, it aims at an efficient use of the resources thanks to the usage of special entities specialized in supervision and in human-machine relationships.

Next, a *product-oriented approach,* which considers three objectives simultaneously: flexibility, reactivity and modularity was presented. To this end, a self-scheduling approach and control approach, in which the products as clients are autonomous and intelligent entities, has been presented. Each product has all the information on its manufacturing process (operation sequence, production rules, priority rule, due date...) and has a direct access to the information of all the other entities. The results are very encouraging when this approach is applied, because the machine utilization rate in both cases (normal case and disruption case) is high. Moreover, using this approach, waiting time is decreased and a near just-in-time control is obtained. The results also show that our approach is able to schedule and control the production system without any prearranged schedule.

Outlines:

With a view to a synchronous production amongst clients and subcontractors, the effort in this study was related to the concept of process. Thus, in the near future, we can hope to be able to solve the problems of process synchronization and optimization. A mathematical model can be considered, which will make possible to locate managing points of a production system. Relevant information will be injected into such points. We think that this model will bring a rigorous base to carry out possible improvements in the management of coherence and to diagnose potential malfunctions.

9 Acknowledgment

Authors collaborate in the framework of Virtual Research Laboratory – Knowledge Community in Production, VRL-KCiP.

The work described in this paper is a part of the SPACS research project that was supported by a grant from the Rhône-Alpes regional council.

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ISBN 978-3-901608-32-2