Modelling methodology for the simulation of the manufacturing systems

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Abstract: Facing an increasingly competitive environment, companies must continually improve the performance of their production systems to respond to consumer demand which is increasingly unpredictable, unstable and with competitive prices. This article is intended as a contribution to finding a solution to an emerging problem in the management of manufacturing flows in recent years where product diversity, shortened lead times and strong competition make the aspect of the 'flow' of goods from supplier to end customer a central one. In this perspective, the aim of this paper is to develop a flexible modelling environment for the simulation and analysis of production systems. This environment enables the decomposition of the production system, by offering generic and modular concepts for modelling the physical processes as well as the control processes to simulate the manufacturing processes as a whole. These concepts are specified and modelled using an object oriented approach such as the unified modelling language (UML).

Keywords: manufacturing systems; manufacturing modelling; model reusability; model replication; simulation; optimisation; control systems; decision-making; performance evaluation; UML; industrial case study.

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1 Introduction

The current production systems are growing in complexity. This complexity is the result of market requirements, competition, quality requirements, not to mention the density and diversity of the processed products.

Poorly controlled, these systems continue to present enormous problems of design, modelling and control (Li and Meerkov, 2009). If in the past they were sufficient to design and manage a production system; nowadays, optimisation techniques, design methods and policy control are often required (Dias et al., 2014).

Control and optimisation of the flows of complex systems require the provision of an optimal model of its dynamic behaviour. However, a dilemma exists between the development of a model too simplistic allowing an easy analysis but removed from its actual behaviour, and a model closer to reality but whose study is too complex or impossible.

In this context, two main methods for analysing and evaluating the performance of a production system are distinguished. One is based on *analytical models* and the other on the *simulation techniques*.

The first method is based on exploiting the properties of *analytical models* used to represent the system. The main models found in literature are based on the use of models from Markov chains (Stewart, 2009), queues (Gautam, 2012), Petri Nets (Huang and Chiang, 2011; Reisig, 2013) and Max + algebra (Declerck, 2013).

If, under certain assumptions, these methods can give the main stationary performance of the system, then their generalisation to complex systems or heterogeneous systems remains a difficult problem (Srivatsan, 1993; Tolio et al., 2002).

One solution to this problem can be seen from the second method namely the *simulation techniques* (Molnar et al., 2009; Wainer, 2009).

Simulation enables studying more complex systems and being more realistic (Pierreval et al., 2007). It is probably one of the most common techniques to analyse the flow of production systems, and to design an appropriate control policy. It is a powerful tool because of its flexibility and its ability to represent any system.

However, if the simulation provides a considerable gain in the modelling phase, then the validation of simulation models remains difficult to generalise to any system (Joschko et al., 2012). In addition, the flexibility of the simulation has its counterpart in the computational cost and programming. Moreover, the validation of a simulator is often hard to achieve because of the difficulty of modelling decisions (Berchet, 2000; Habchi, 2001; Nicoletti et al., 2014; Pierreval et al., 2007).

Gaps and limitations of the simulation are of two kinds: those related to the modelling approach (Delen, 2009) and those related to the use of computers (North and Macal, 2009; Schwede et al., 2009). As part of this research, the problem of modelling received a special attention in order to overcome the difficulty of reusing existing models and concepts, the difficulty of refining existing models without redoing them entirely, and the difficulty of modelling the control system as a full system.

Following an analysis of production systems in order to simulate them, the criteria have been identified for improving the effectiveness of the modelling approach. This analysis essentially involve decomposing the production system, and proposing generic and modular concepts for modelling a physical process and control to simulate the manufacturing process as a whole.

These concepts are specified and modelled using the object oriented approach. A model is built using UML (Dennis et al., 2012; Larman, 2012).

2 Production systems

A production system is generally viewed as the combination of a set of resources interacting to achieve a production activity (Li and Meerkov, 2009). It must perform the essential functions of manufacturing, transportation and storage.

Indeed, the production is performed by a sequence of operations of processing, transfer, assembly and disassembly by exploiting the available resources (machines, transfer systems, etc.) in order to transform raw materials into finished products leaving the system.

Production systems can be very complex systems and difficult to manage in view of all their functional components (manufacturing, maintenance, management, control, etc.) (Bellgran and Säfsten, 2010). Several approaches were considered in order to better understand how they work.

2.1 Components of a production system

From a systematic perspective, it is conventional to decompose the *Enterprise System* in three cooperating systems (Le Moigne, 1994), namely: The physical system, the information system and the decision system.

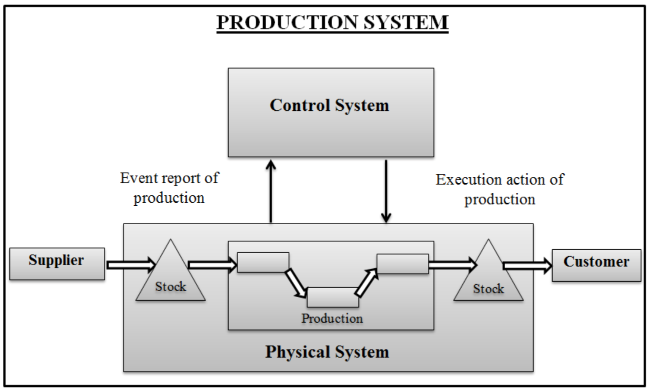
The physical system, also known as operating system or technological system, acts on the products by performing transformations, controls, storage and handling operations. The physical system can be organised in different ways: in flexible lines, into homogeneous sections, in transfer lines, in production cells, etc.

The information system essentially performs the acquisition, processing, transmission and storage of information coming from the environment of the production system (physical system), but also from the system itself. It serves as a liaison between the decision-making system and the physical system.

The decision system, also called driving system or control system, is intended to control the evolution of the physical system. It decides according to the behaviour of the physical system, the state of the environment and objectives that have been assigned to it. This system covers all activities of planning, coordination, supervision, monitoring, stimulus control and assurance.

If this decomposition is valid for the system 'Enterprise' and provides the means of its analysis, it is, however, less suitable for the production system and its modelling. Indeed, in a production system, subsystems of information and decision have no independent existence apart from each other. Together they constitute what has been called the control system (Trentesaux, 2009). Thus, it is more consistent with reality to consider the production system as the combination of a physical system and a control system (Figure 1).

Figure 1 Decomposition of the production system



In the following section, the study of the physical system of classification, organisation, modelling and evaluation perspective will be focused on.

2.2 *Classification of production systems*

Classification of production systems calls for consideration of their organisations, their types, their characteristics and therefore their use cases. However, it is difficult to establish a complete classification of all the features, published in literature, regarding a production system. Therefore, a brief overview will be provided on classifications that provide a summary review on aspects that are relevant in the context of this study.

In this context, two classifications of production systems found in the literature (Bellgran and Säfsten, 2010; Li and Meerkov, 2009; Monden, 2012) help locate precisely the context of this work: one depending on the nature and volume of physical flows in the system while the other according to the control mode.

Classification according to the nature of the physical flows is based on the nature of the physical system and the volume of products manufactured by the latter. Within this framework, three main types of systems have been distinguished: continuous flow systems, discrete flow systems, hybrid or discontinuous flow systems.

Classification according to the control mode is closely related to the control strategy used. Indeed, lying at the operational level and based on the trigger mode of production, this classification separates systems operating at *pulled flows* from those operating at *pushed flows*.

Under the first classification, the production at discrete flow and more particularly in the production of medium and large series received significant consideration. Indeed, this is the category of production where the problems of flow control and more particularly the problems of allocation of production capacity are more numerous and complex.

According to the second classification, we are in the framework of a control where the two modes of management of pushed and pulled flows are present. In the following, production systems at discrete flows will be focused on detailing their organisation, their modelling and the necessary tools for their analysis and their evaluation.

3 Conceptualisation of production systems

The new market constraints raise a number of problems that must be taken into account from the start of the design phase of the production system. These constraints are:

- *The heterogeneous nature* of the main physical flows of production system, the elements constituting their flows may be of different types (screws, nuts, washers, etc.) elementary or compound (components, subassemblies, and assemblies) and of variable rates (parts, batches, serials).
- *The optimisation of production areas* (areas of transformation, storage, transfer) to minimise the production cycles and production times.
- *The complexity of the production function* that handles both the manufacturing processes and the control processes.

In this section, an analysis of the production system is proposed. This analysis will identify basic concepts wanted to be generic, for analysis and modelling of the production system with the aim of simulation.

3.1 *The physical system*

The aim of the physical system model is to faithfully reproduce the behaviour of the production system, in particular the interactions with its environment and more particularly with the control system. The *physical system* consists of four main types of objects: the *system*, *resources*, *products* and a set of transformation *operations* required to produce the finished product.

- *The system*

The *system* ensures the structural representation of the physical system. Elementary components are used to associate a set of *operations* to *resources* for each type of transformation: Shape-Time (Production), Space-Time (Transport) or Time-Time (Storage). The *system* is used to model these different types of transformation and so to construct the physical system.

- *The resources*

Resources are the means of production available to the physical flow (products). They can be identified by two types: the main resources and auxiliary resources.

The *main resources* are *the active resources* that have some autonomy from the rest of the system. For example machinery, robots, operators, transfer means, etc.

The *auxiliary resources* are *the passive resources* that conditions the main resources to perform an operation, and which are not directly involved in the development of an operation. For example stocks, pallets, etc.

In some cases, human operators can be considered as main resources (control operations, weighing, packaging, etc.) and in other cases as auxiliary resources (control of a machine).

- *The products*

The products form the physical flows. These flows consist of all entities that circulate in the system and which undergo alterations in the physical system. They include raw materials, parts, batches, sets, products, etc.

The entities comprising the flows are the source of the activities of the main resources of the system. They constitute the system load. The formalisation of the system load passes in general by the use of the *process plans* and the *bills of materials*.

The same component can appear in multiple scales and in several bills of materials. Furthermore, any element of flow follows a process plan whether or not known a priori and belongs to a bill of materials.

- *The operations*

The operations associated with a resource can be of four types (Bellgran and Säfsten, 2010): production operations, transport operations, storage operations and check/control operations.

The operations performed by the main resources are only able to modify the physical state of a product. They can be of two types: operations with value and operations without value.

The *operations with value-added* might involve machining, assembly, welding, packaging, etc.

The *operations without value-added* can be storage, control, transfer, etc.

According to this view, a physical system is a set of resources that perform transformation operations on products.

3.2 Modelling of the physical system

The physical system is a generic and customisable framework, which can be expanded depending on the specificities of resources to be modelled and the level of detail desired. It permits a modelling close to the mental perception of users to manipulate objects close to reality. The modelling approach proposed falls within the framework of models based on generic objects (Essaid et al., 2011).

In this case, the physical system will be modelled using generic concepts named: Resource, Operation, Product and System.

The *Resource* mainly performs four basic operations: receiving, transformation, supply and check/control. It has all the basic structural and behavioural features of a production system: Production, Storage, and Transportation.

The *Operation* represents the set of transformation operations required to produce the finished product.

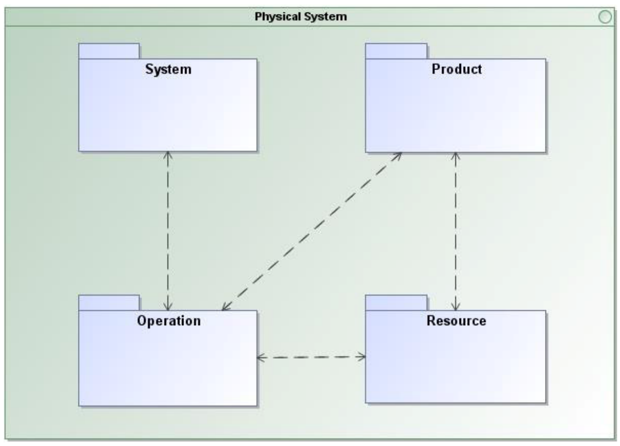
The *Product* represents the physical flow circulating among resources. It may be a piece, a batch, a manufacturing order, etc. It is this structure which will include information related to products such as process plans, operating time, etc.

The *System* is an elementary component for modelling different types of transformation operations to construct the physical system.

Thus, the physical system has been specified by a set of four *packages* corresponding to the four mentioned concepts (Figure 2):

- resource package
- operation package
- product package
- system package.

Figure 2 Physical system package (see online version for colours)



3.2.1 The resource concept

The analysis of physical systems, in terms of simulation, is used to see that all resources are considered to be structurally and functionally identical.

To build a modelling approach taking into account the criteria defined above, a generic structure is proposed capable of representing a physical system, made of five hierarchical levels: the basic resource, the station, the cell, the island and the workshop.

The *basic resource* (machine, operator, stock, etc.) corresponds to the lowest level of the structure. It is capable of performing a production operation, storage, or transportation. The internal flow consists of individual parts.

The *station* is a limited association of basic resources (a stock, a machine and operator). The internal flow is also made of individual parts.

The *cell* is a combination of several stations, and eventually a synchronous transfer system (conveyor). It is characterised by its autonomy over a given period of time. Its internal flow (set or subset of products) is formed by assembling components.

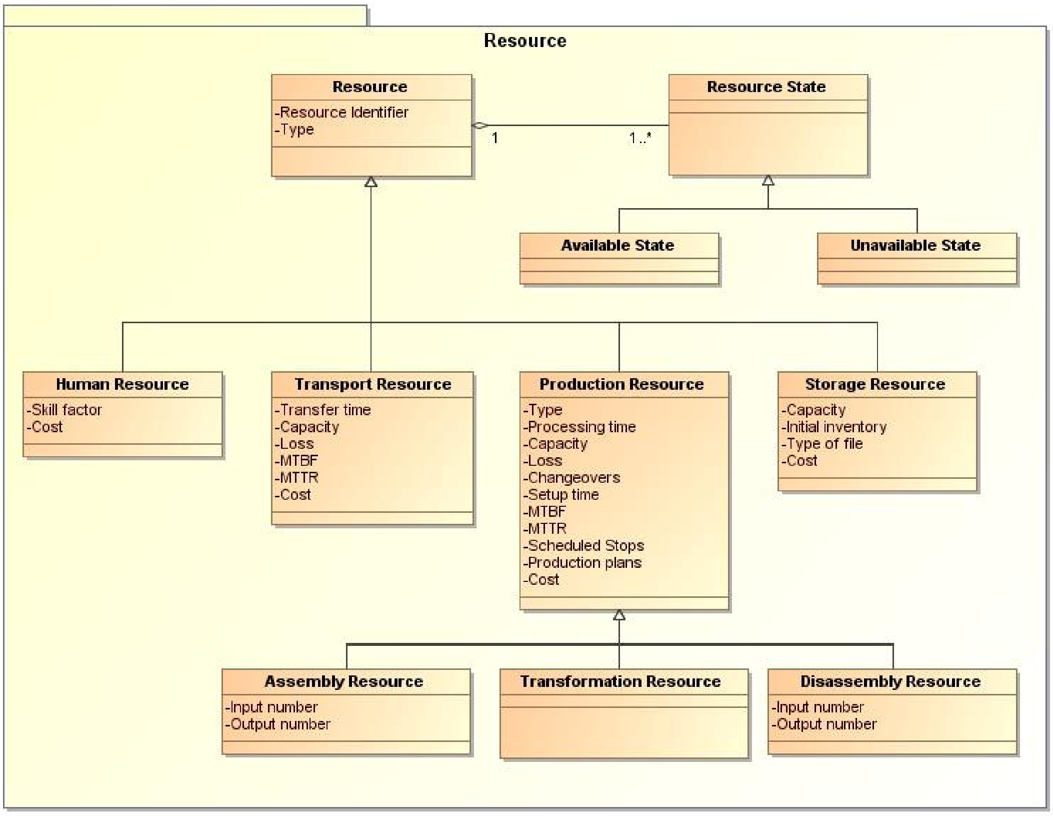
The *island* is defined as a set of cells associated with a transfer network not necessarily synchronised (a wire-guided trolley system). The internal flow is usually the batch.

The *workshop* is a set of islands associated with a transfer system (trolleys or shuttles). It corresponds to the highest level of the structure. The internal flow consists of batches or groups of batches (sets).

- *Resource package*

The package resource (Figure 3) contains specific data to the Resource. It leads first to identify the resource, and to inform the actual data that will be used to calculate the indicators.

Figure 3 Resource package (see online version for colours)



- *Behaviour of a resource*

All the resources of the physical system have basically two identical aspects; first an aspect machine which is translated by the operational behaviour (transformation, transfer, control), and second a stock aspect which is translated by an operation of temporisation intended for the regulation of the production.

The stock aspect is present on a machine in case of a downstream blockage of the production. It thus appears that the resources of a physical system are structurally and functionally identical.

Therefore, the functional behaviour of a resource can be expressed in a generic way in four main operations: the *receiving, the check/control*, the *transformation* and the *supply*. This behaviour is valid whatever the resource is and whatever its hierarchical level is.

- The *receiving* operation consists of obtaining one or several entities to be transformed. The realisation of this operation assumes that the part to be received is available, that the capacity of the concerned resource is not saturated and that this resource is ready for the receiving.

- The *check/control* operation consists of inspecting the entity to be transformed. It is a quality control operation whose purpose is to determine whether the product being manufactured meets the established design standards and specifications.
- The *transformation* operation is only capable of modifying the physical state of a product. It consists in retaining the entity for a certain time '*T*' defined by the process plan of production. The activity of the resource, beyond '*T*', is considered as a blockage of the resource.
- The *supply* operation consists of releasing the concerned resource and in supplying the entity transformed in the consecutive resource and defined by the process plan of manufacturing. The realisation of this operation supposes that the following resource is ready to receive it.

Every resource of the physical system can be modelled. Built according to this approach, the model is partially a recursive and hierarchical network of several resources.

- *States of a resource*

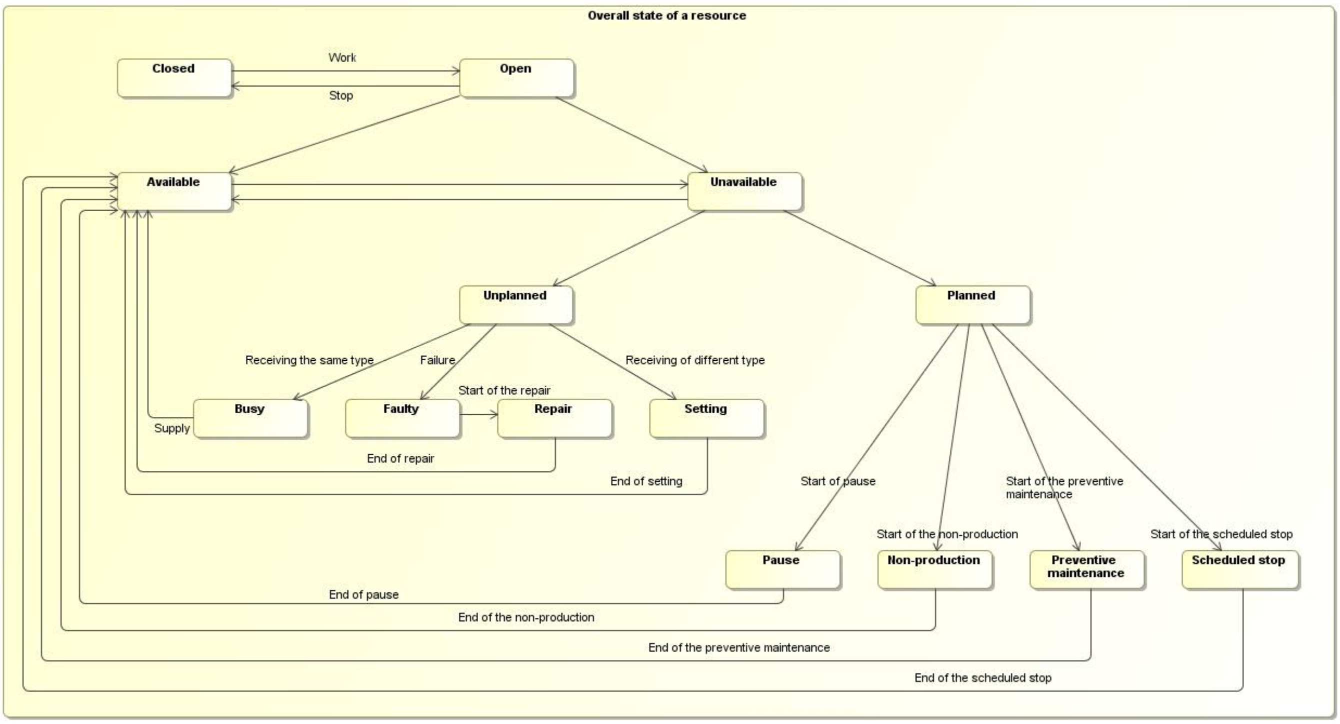
A resource passes successively, in a deterministic or random way, through a certain number of different phases or states. The state corresponds to a particular situation in a certain time. It is defined by a set of characteristic variables representing the various facets of the resource: the state variables.

The state of a resource is defined by the set of values taken by each of its state variables. The production process results from the interactive succession of a number of states, through which pass the various resources which consist the physical system.

It is possible to describe the behaviour of a given resource and evaluate its performance using various indicators related to its states. This performance will be used later to control the resource during the simulation. The number of states associated to a resource depends on its adopted level of detail.

To describe the behaviour of a resource and estimate its performance with the aim of its control, three states have been defined (Figure 4): open state, available state and unavailable state.

Figure 4 Overall state of a resource (see online version for colours)



The *Open State* translates the commitment or the non-commitment of a resource in the process of production. This leads to two states (*opened* and *closed*) and two sub-states (*available* and *unavailable*).

The *Unavailable State* corresponds to either a planned state (*pause, non-production, preventive maintenance, scheduled stop*) or unplanned (*busy, faulty, in repair and in setting*).

The *Available State* is synonymous with a productive resource adding a positive value.

3.2.2 The product concept

The modelling of the production system implies, likewise, the modelling of the second type of object that establishes the physical flow. The product is the object representing the element of the physical flow. This flow is made of all the entities which circulate in the system and which undergo transformations at the resources. It can be defined by a unitarian object or an assembly of unitarian objects according to a recursive process.

The elements which are part of the physical flow are different in nature and can be classified into different types: single part, product, batch and serial.

The *single piece* corresponds to a component, part, etc.

The *product* is very often made of an assembly of a set of generally different single parts. It can correspond to a single part.

The *batch* is formed by a set of single parts of identical products.

The *series* correspond to a set of different batches, it is characterised by the running order of batches on the production resources.

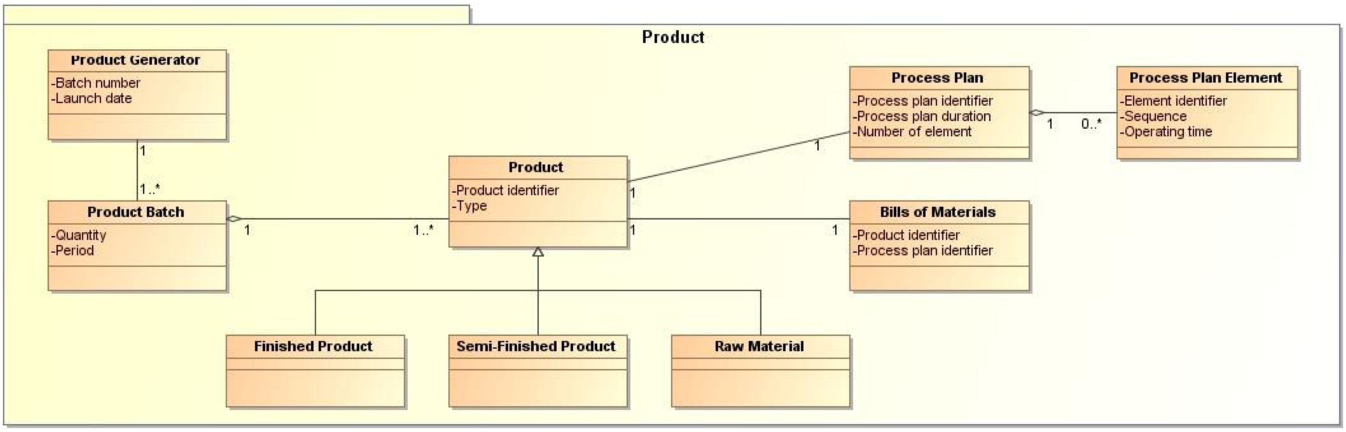
According to the point of view of the simulation and for the purpose of performance evaluation as well as the control of the production system, it is necessary to follow the elements of the physical flow in both time and in the space through the physical system. Thus, the entities taking part in the physical flow will be followed over time and space through their characteristics.

In addition, the evaluation of the performances and the control of this flow require the establishment of indicators and the assignment of variables that permanently identify the state of the flow. The characteristics as well as the state variables making possible the calculation of relevant performance indicators, which will be the entries of the control process of the production system.

- *Product package*

The product package (Figure 5) contains specific information on the product. This information represents the technical data such as process plan and bill of materials of the entity, and maintains a vision of the status of the physical system, both from the point of view of the product flow and resources that represent physical objects production flow.

Figure 5 Product package (see online version for colours)



However, it also identifies the product and informs the actual data that will be used to calculate the associated indicators.

3.2.3 The operation concept

A physical system can be regarded as the combination of several operations. The physical organisation of a production system focuses on the basic resources (machinery and stocks) which correspond to the lowest level of the physical structure.

The physical system is then seen as a network of basic resources interacting with each other and invoking operations of Production (transformation, assembly and/or disassembly), Transport, Storage and Check/Control connected by a path consisting of machinery, stock and transportation.

- Package operation

The operation package (Figure 6) groups the generic operations defined by the system. These operations represent the association of one or more products with one or more resources during a certain period.

3.2.4 The system concept

- *Package system*

The package system (Figure 7) creates the generic processes established by the physical system. These processes represent the association of one or more operations with one or more resources during a certain period.

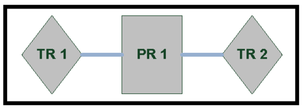
- *Rules for construction of a system*

For the study of production systems, the rules of construction have been defined in order to construct models of production systems and to better understand how the system works.

Basic modules have been proposed which makes possible representing each entity within such systems. It is now a question of assuring the consistency of the resources with the production flow. This consistency can be guaranteed only by the statement of assembly rules of these *Resources*.

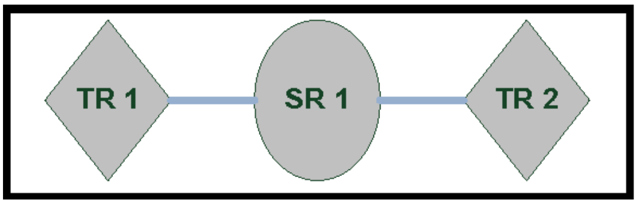
The resources are governed by rules of succession set below:

- a *Production Resource* is necessarily followed by a *Transport Resource* (Downstream transport)
- a *Production Resource* is necessarily preceded by a *Transport Resource* (Upstream transport)



TR : Transport Resource
PR : Production Resource
RS : Storage Resource
: Physical Flow

- a *Storage Resource* is necessarily followed by a *Transport Resource* (Downstream transport)
- a *Storage Resource* is necessarily preceded by a *Transport Resource* (Upstream transport).



And by inference:

- a *Transport Resource* may be followed by a *Storage Resource* or *Production*.
- a *Transport Resource* may be preceded by a *Storage Resource* or *Production*.

Figure 6 Operation package (see online version for colours)

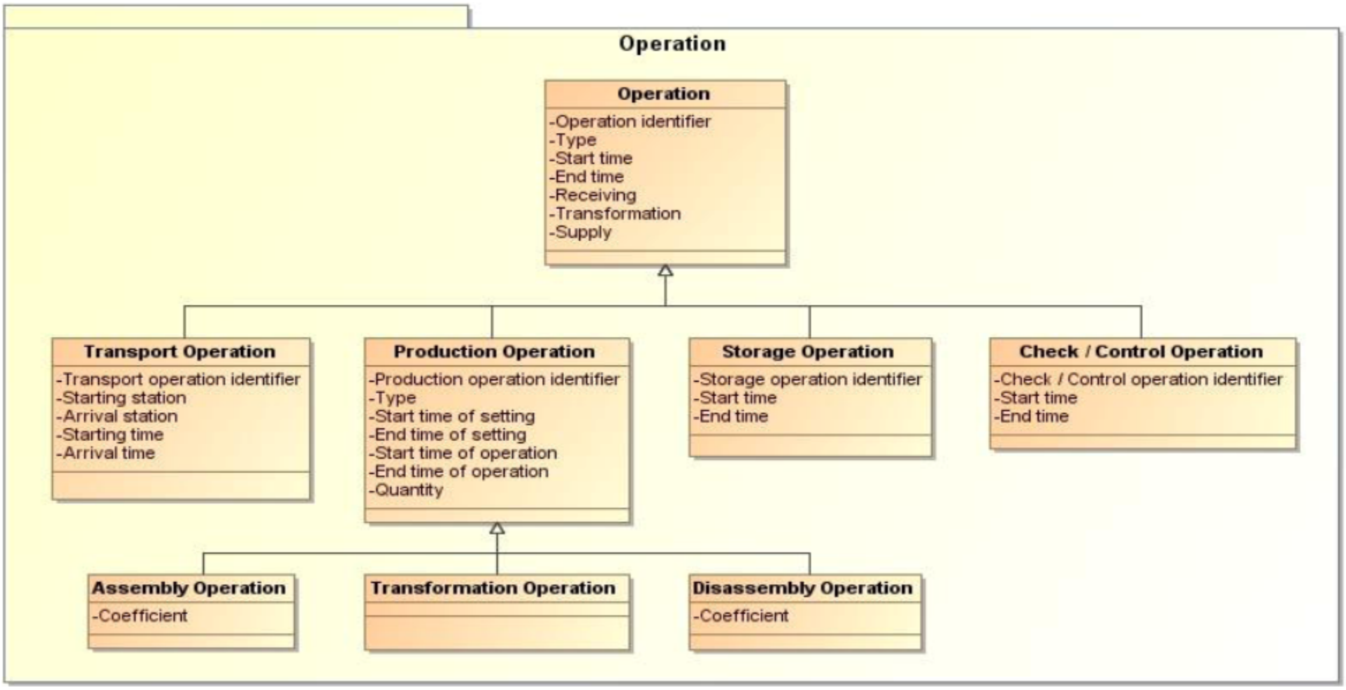
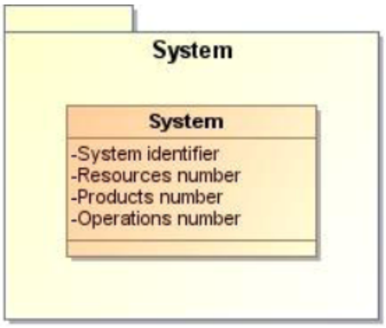


Figure 7 System package (see online version for colours)



In addition, a *Transport Resource* is exclusively downstream or upstream of another resource. Also a *Transport Resource* cannot be at the same time upstream transport and downstream transport of the same process.

- *Synthesis*

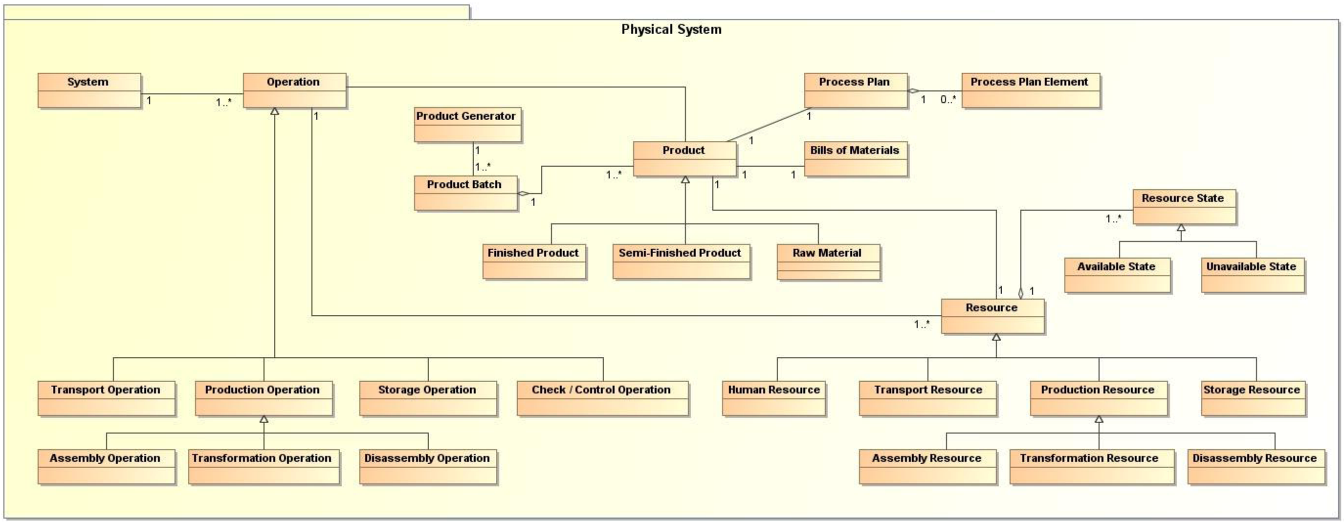
The overall physical system package (Figure 8) is as follows:

3.3 The control system

After characterising the physical system concepts, the control system will be subsequently presented. In this section, the control system will be described in a frame of reference systematic.

This framework capacitates then to establish a model of the control system, leading to its formalisation.

Figure 8 Physical system package (see online version for colours)



3.3.1 The control

The control is used to dynamically decide relevant instructions to be given to a system subjected to disturbance in order to reach a given objective described in terms of control performance (Trentesaux, 2009).

In the framework application of the production of goods and services, Baker (1998) proposes the following definition: "Factory control is defined as the actuation of a plant to make products, using the present and past observed state of the plant and demand from the market".

Dilts et al. (1991) meanwhile offer the following definition: "the control system of an automated manufacturing system coordinates and directs the parts handling and processing activities that transform raw materials into finished products".

Several definitions are available in Darmoul et al. (2013), Trentesaux (2009) and Zbib et al. (2012).

3.3.2 Typologies of the control systems

A control system (Adam et al., 2011; Ounnar and Pujo, 2012; Pujo et al., 2009) can basically be organised according to two types of sub-systems: centralised and not centralised (Mesarovic et al., 1980; Mintzberg, 1982).

We have opted for the structuring of Mesarovic et al. (1980), which characterises a control system according to *organisations* invariant on a given horizon (Camalot, 2000; Monteiro, 2001) and *interaction modes* designed for a given organisation.

- *Organisation*

Usually two mechanisms of organisation are distinguished (Meinadier, 1998; Mesarovic et al., 1980; Mintzberg, 1982): a mechanism of *vertical organisation*, referring to the notion of *hierarchy* between entities. A mechanism of *horizontal organisation*, referring to the absence of any hierarchy between entities. This organisation can be described as *heterarchical* structure where entities are therefore at the same hierarchical level (Duffie and Prabhu, 1996).

A relatively common typology is based on the degree of hierarchy of the organisation considered by report to the degree of heterarchy. Thus, four classes of organisation have been considered (Trentesaux, 2009):

- *Class I*: This typology includes the centralised control systems (Figure 9).
- *Class II*: It includes the non-centralised control systems whose organisations are purely vertical. They are qualified as purely hierarchical or hierarchical in a strict sense (Figure 10).
- *Class III*: It includes the non-centralised control systems presenting hierarchical and heterarchical organisations. They are qualified as heterarchical in the large sense (Figure 11).
- *Class IV*: It includes the control systems whose organisations are purely horizontal. They are qualified as purely heterarchical or heterarchical in the strict sense (Figure 12).

Figure 9 Class I: centralised organisation

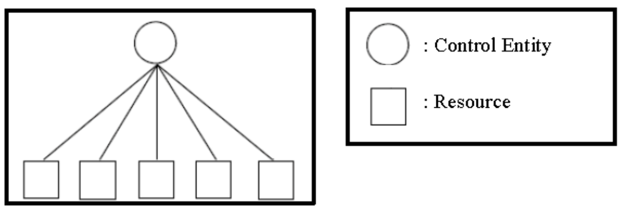


Figure 10 Class II: hierarchical organisation in the strict sense

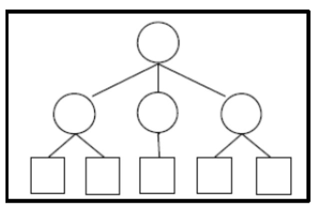


Figure 11 Class III: heterarchical organisation in the wide sense

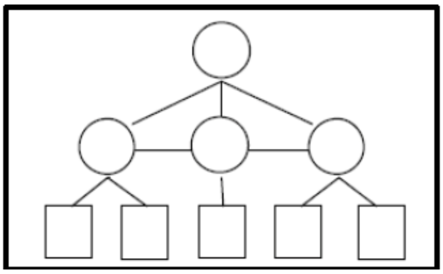
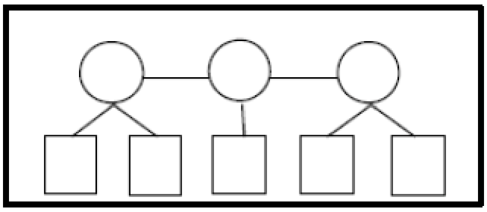


Figure 12 Class IV: heterarchical organisation in the strict sense



Vertical links are the links of hierarchical dependencies, and horizontal links are links of heterarchical relationships.

- *Interaction modes*

Interaction modes correspond to the external processes of interaction between entities (Le Moigne, 1994). These modes of interaction are based on hierarchical links or heterarchical links.

Two entities are organised vertically, i.e., that the entity hierarchically inferior cannot ignore information that the hierarchically superior entity communicates to it. This information is considered as constraints to be respected.

Two entities are organised horizontally, i.e., that the information exchanged is not constrained and that it may not be taken into account. Patriti et al. (1999) adopts this view by defining interaction directives (hierarchical relations) and not directives (heterarchical relations).

It has been decided to use heterarchical systems. This type of systems has many advantages (Pujo et al., 2009; Zbib et al., 2012).

3.3.3 Modelling approaches of the control system

To model a control system, several approaches are reported in the literature. Patriti et al. (1999) distinguishes four types of modelling: the multi-agent systems, the heterarchical systems, the bionic manufacturing systems and the holonic manufacturing systems.

In this typology there is confusion between:

- Structural criteria based on *heterarchy.*
- Conceptual criteria based on agents and holons
(A holon corresponds to an element of an autonomous and cooperative manufacturing system dedicated to the production, transport, storage and/or the management of physical objects or informational (Van Brussel et al., 1998)).

For this reason, the proposal from the following typology (Trentesaux, 2009) has been chosen:

- *Approach by process*

The approach by process consists of defining entity models oriented towards the temporal dimension of the processes and activities.

This approach leads naturally to the development of heterarchical control systems (Pujo et al., 2009; Zbib et al., 2012) (by proposing models of control entities) since it represents the identification of control functions which dominates at level the system design (the control functions are then assigned to entities).

This approach leads to different types of control entities: Control Center, I-machine, Integrated Station of Control, Autonomous Entity of Control, Station Manager, etc.

- *Holonic approach*

A holarchy consists of a set of autonomous holons that cooperate to achieve a goal or objective (Van Brussel et al., 1998).

In the field of production management, it is common to define a Holonic Manufacturing System (HMS) as a holarchy which integrates the entire process plan of manufacturing activities from order booking through design, production and marketing to realise the agile manufacturing enterprise (Adam et al., 2011).

The adequacy between this modelling approach and the heterarchical control concept comes primarily from the possibility to model any type of class of control systems and any type of production actor (Adam et al., 2011; Bongaerts et al., 2000; Ounnar and Pujo, 2012).

- *Multi-agent approach*

An agent is essentially an autonomous software object, finalised and able to communicate (Huhns, 1987). An agent system is designed to achieve the goals programmed in advance by its designer (Borangiu et al., 2013).

The multi-agent systems constitute with the parallel intelligence a field of distributed artificial intelligence (DAI; Darmoul et al., 2013).

The adequacy between an agent and heterarchical control concept arises from the fact that a minimal definition of an agent, which is an entity that perceives its environment, acts on this one and behaves rationally (Borangiu et al., 2013; Darmoul et al., 2013). Therefore, it is easy to adapt this approach to heterarchical control.

- *Synthesis*

The holonic approach differs from the multi-agent by the fact that the concept of holon is recursive (Adam et al., 2011). However, it complements this approach by considering that in the manufacturing system, machines and humans can be 'colleagues' (Baker, 1998). The notion of holarchy covers three classes of organisation (Class II, III and IV) (Bongaerts et al., 2000), while the multi-agent approach can apply to all classes (Borangiu et al., 2013).

The multi-agent approach favours a distribution of control (DAI). On the other hand, in the holonic approach or by process, the decentralisation of control is favoured but not systematic. The various control processes are distributed and are therefore difficult to localise (Darmoul et al., 2013).

3.4 Modelling of the control system

During the simulation of a production system, the control process necessary for the maintenance of the system on its projected path must be considered with all its real aspects.

Control expresses the relationships between actors makers, resources, products, etc. These relationships correspond to two types of rules: The rules of precedence given by the process plans, the bills of materials, etc. Data management rules by setting priorities, hazard management, scheduling, etc.

The precedence rules (process plans and bills of materials) define the manner in which the physical flow crosses the resources (logical sequence of operation). These rules are static in nature; they are assigned to products.

On the other hand, management rules are of dynamic nature. They evolve over time according to the state of the resources in the physical process. These rules are assigned to resources because generally implemented actions are performed on resources to improve the performance of the production process.

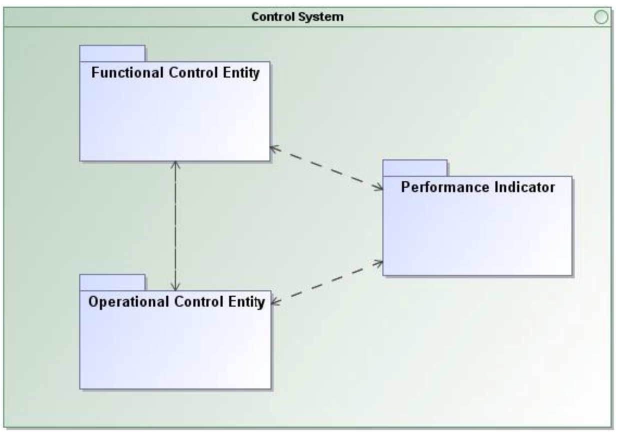
To model the control system, a generic model has been proposed based on three concepts: operational control entity (OCE), functional control entity (FCE) and performance indicator.

Thus, the control system is specified by a set of three packages corresponding to the three mentioned concepts (Figure 13):

- OCE package
- FCE package
- performance indicator package.

However, before defining these concepts, the control environment in which these concepts will evolve must be developed. This environment makes possible the organisation and maintenance of the control system.

Figure 13 Control system package (see online version for colours)



3.4.1 Control environment

During the simulation of a production system, the control process, necessary for the maintenance of the system on its projected path, must be considered with all its real aspects. The control can exist only if the system is in motion; that is to say, that the system state varies mainly according to two factors: space and time.

In addition, the control process is constructed by the introduction of various decisions taken at different times and different points of the system. The decisions to be taken and implemented depend on the different objectives to achieve which are defined according to the hierarchical levels of the industrial system.

To conceptualise and integrate the control in the simulation process, the general control environment must first be represented. A heterarchical structure has been chosen due to the potential of its performance (Zbib et al., 2012).

Hierarchical models developed during the 1970s met the needs of industry. The advantages of the hierarchical approach are essentially: the quality of the structuring, integration and process optimisation (Vernadat 2009, 1996).

Since the 1990s, increased competition, product diversification, market volatility, etc. made purely hierarchical approach (Class II) and centralised (Class I) partly unsuitable (Duffie and Prabhu, 1996). The heterarchical approach (Class III and IV) enables a priori to meet certain expectations, since it is characterised by greater responsiveness, better scalability and better alignment with the new production structures (Trentesaux, 2009).

However, reduction of hierarchical relationships generates several disadvantages such as: the emergence of conflicts, the asynchrony between entities, instability (Bongaerts et al., 2000), including those relating to visibility reduction in more or less long term that are related to the guaranteed performance.

To remedy this, a heterarchical structure has been adopted in the wide sense (Class III), where the advantages of the hierarchical structure has been in the strict sense (Class II), in addition to the agility provided by the heterarchical structure in the strict sense (Class IV). This agility which is translated in terms of responsiveness and scalability is now considered the current object of competition between companies.

This type of structure offers many advantages in terms of integration of objectives. It authorises taking into account local objectives. It also provides the collaborative aspect between the various entities of control of a same heterarchical level, by taking into account during the decision-making, objectives of the other control entities (as constraints), because of the hierarchical structure.

To model this heterarchical control system (Class III), the approach by process has been relied on. The originality of the latter is to emphasise the temporal dimension of control activities, and highlighting the triptych (state, assessment, action) and decision-making process (information, design, decision, assessment, etc.).

It therefore appears appropriate to model the control process by a *Process Approach* in view always, of its integration at the approach of simulation. Therefore, the *Environment Control* has been recorded (Figure 14) in a global model defined by three dimensions.

3.4.2 The concept of a control entity (CE)

The environment of the control process showed the existence of entities arranged at different hierarchical levels essential to control the system. These entities that are generic and capable of controlling other system entities are required to define and implement.

Entities have been used to designate a set of sub-systems capable of decision (Chi and Turban, 1995; Pétin et al., 1998), autonomous and self-organised.

Thus, this entity called a *control entity* (*CE*) (Figure 15) is an organised and independent structure having a decision-making power, associated with an entity to control (Physical Systems, CE) and with a set of resources necessary for the establishment of actions to achieve one or more objectives within the overall strategy of the company.

Figure 14 Control environment

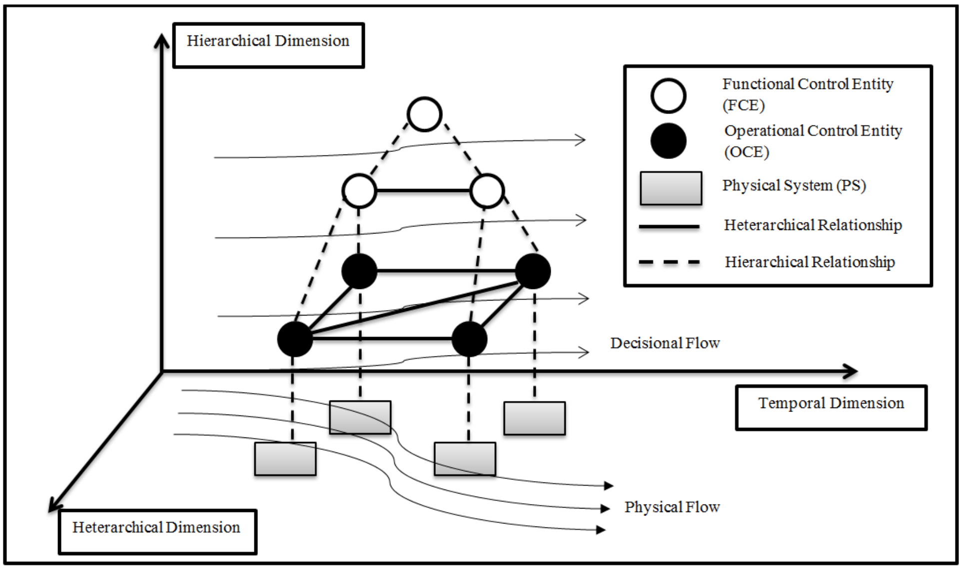
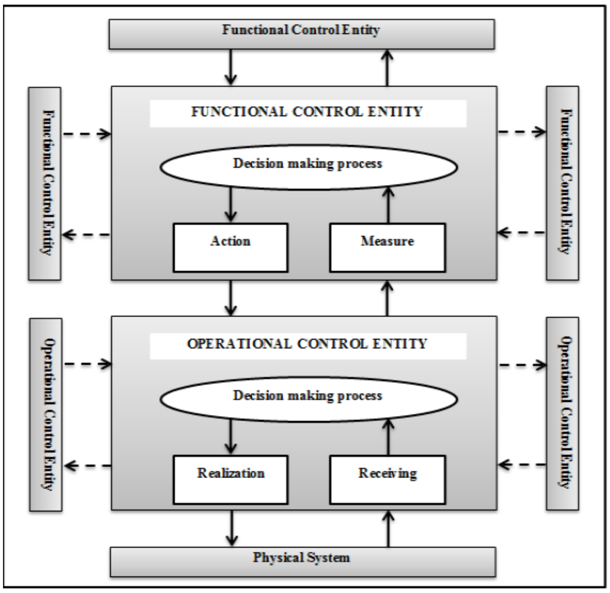


Figure 15 Control entity



By means of this entity, the control in the simulation process can be introduced.

A *CE* has its own margin for interpretation (autonomy), but must be consistent permanently with the overall strategy of the company according to the three dimensions of the Control Environment. This consistency is achieved through hierarchical and heterarchical relationships each of which has its own decision-making processes. The modelling of these relationships has been in particular worked on.

The research works that model these hierarchical and heterarchical relationships are based on the same decision-making process. This approach is neither appropriate nor optimal, since the control of the production system represents a broad field where it is difficult to model all the components (Resource, Product, and CE) and hierarchical levels through the same process.

The approach proposed is to model the heterarchical and hierarchical relationships between the *CE* of different hierarchical levels and the physical system by means of two decision-making processes. These processes will be formalised using two *CE*: a *CE* for the operational level and another one for the functional level.

3.4.2.1 The concept of operational control entity (OCE)

As part of production systems, an OCE corresponds to a control unit of resources.

The modelling of vertical relationships between the OCE and Physical Systems has been especially worked on, as well as the horizontal relationships between different OCE. Likewise attention has been given to highlighting the impact of design parameters and operating on the overall performances to identify the best settings corresponding to a given objective.

The role of an OCE is mainly to dynamically detect and control with a reactive scheduling the physical system, and to manage the overall consistency of local decisions. The data taken into account to achieve the reactive scheduling comes from state of resources and from the actual load of the physical system.

The detection and the reactive scheduling is an event approach triggered, for example, by the emergence of new production orders.

- *OCE package*

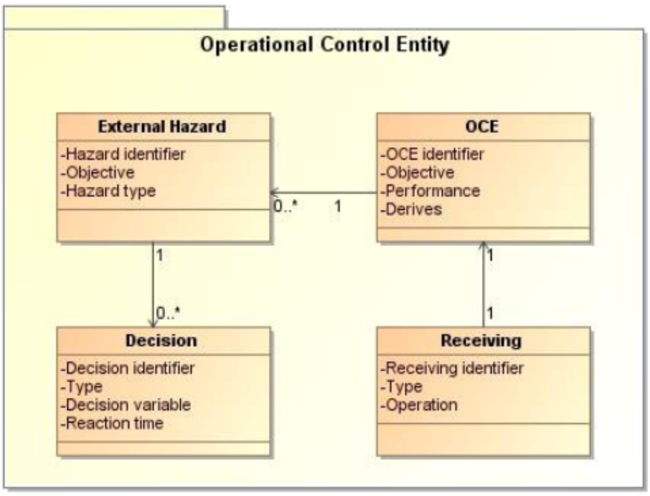
The *OCE* package (Figure 16) is defined as follows:

- *Decision-making process of the OCE*

One aspect that has been considered essential is the one related to decision-making. The decision-making process of the OCE comes down to three stages of evaluation:

- choice of OCE responsible for controlling the realisation of a future operation
- choice of the next production order among those allocated to the OCE for which the current operation should be performed in time of the current operation
- choice of the next production order of which the realisation of the operation in progress will be allocated to an OCE.

Figure 16 Operational control entity package (see online version for colours)

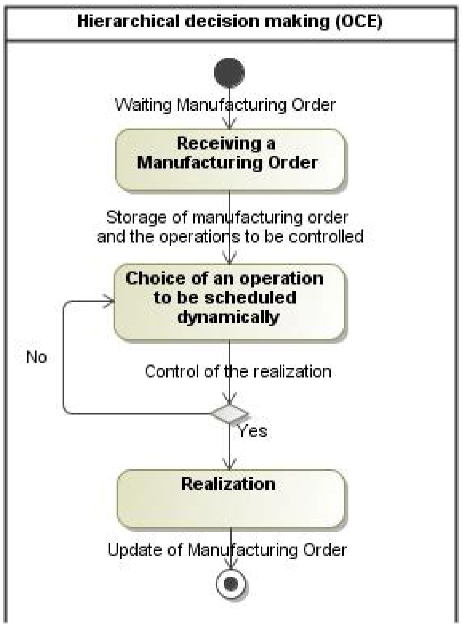


The OCE implements the following decision-makings processes:

- *Hierarchical decision-making process*

The process of hierarchical decision-making enables to control the execution of an operation using a behavioural model of the physical system resources component. This model described using an activity diagram incorporates modes on and off the resource and its functional specificities. This process (Figure 17) is activated when an operation has been received by an OCE to be performed by the resources it controls.

Figure 17 Hierarchical decision-making process (OCE) (see online version for colours)



- *Heterarchical decision-making process*

The heterarchical control process allows distributing between the OCE the various operations to be dynamically scheduled, basing on production goals, process plans, dates of availability and need of production orders.

This process permits to integrate the precedence constraints between operations and the feasibility constraints of operations on the resources. It is activated as soon as the control of the realisation of an operation comes to an end and as soon as the corresponding order of manufacturing is not closed. This process involves an OCE Source (seeker service offering) and a set of OCE Target which potential contractors respond to the tender. The internal process of heterarchical decision-making of the OCE is detailed in Figure 18.

3.4.2.2 *The concept of functional control entity (FCE)*

The FCE role is to control the OCE by a reactive process (approach by event type), based on the decision-making process represented by the loop '*Assessment-Decision*'.

- *FCE package*

The *FCE* (Figure 19) package is defined as follows:

- *The decision-making process of the FCE*

The control process of the FCE involves four main steps: measurement, evaluation, decision, and implementation of the action plan.

Figure 18 Heterarchical decision-making process (OCE) (see online version for colours)

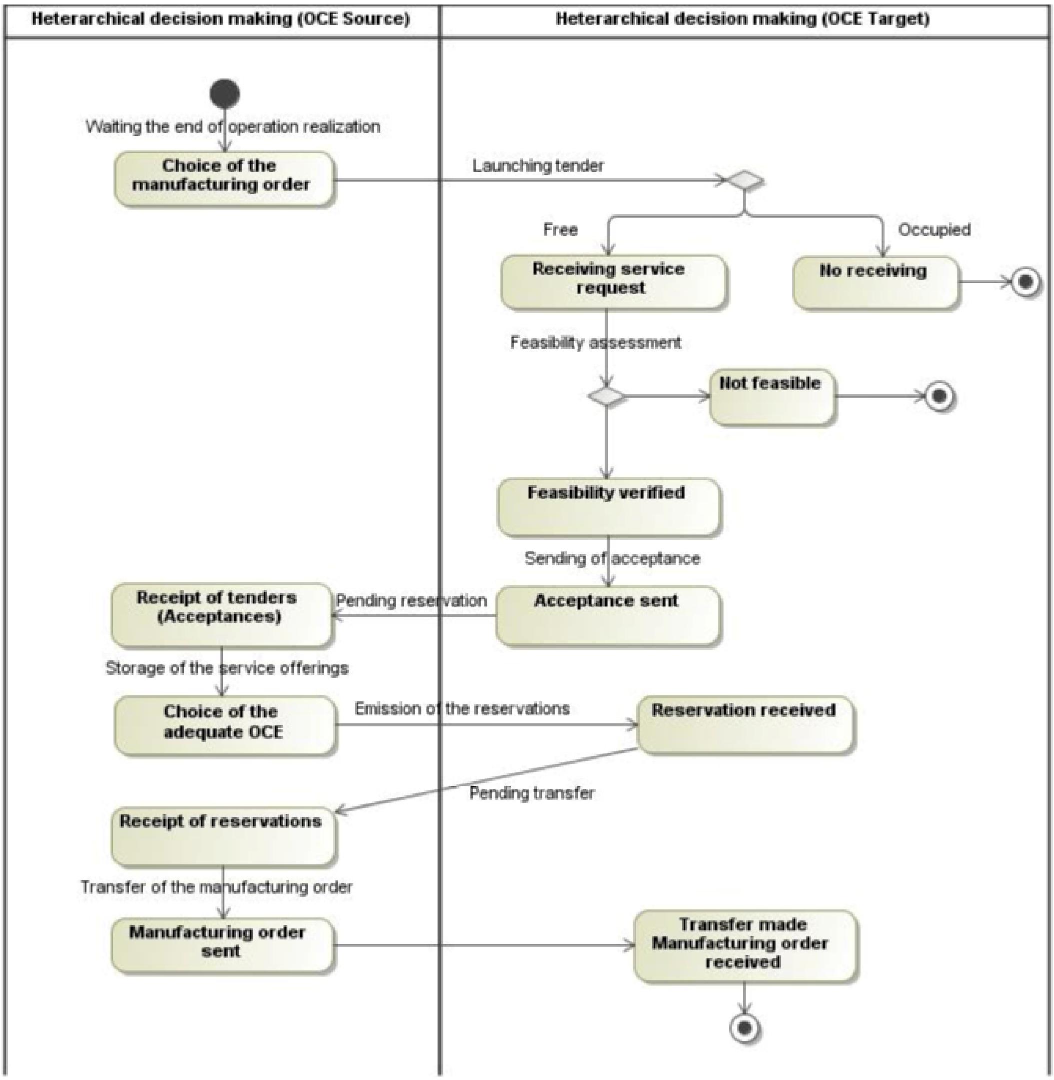
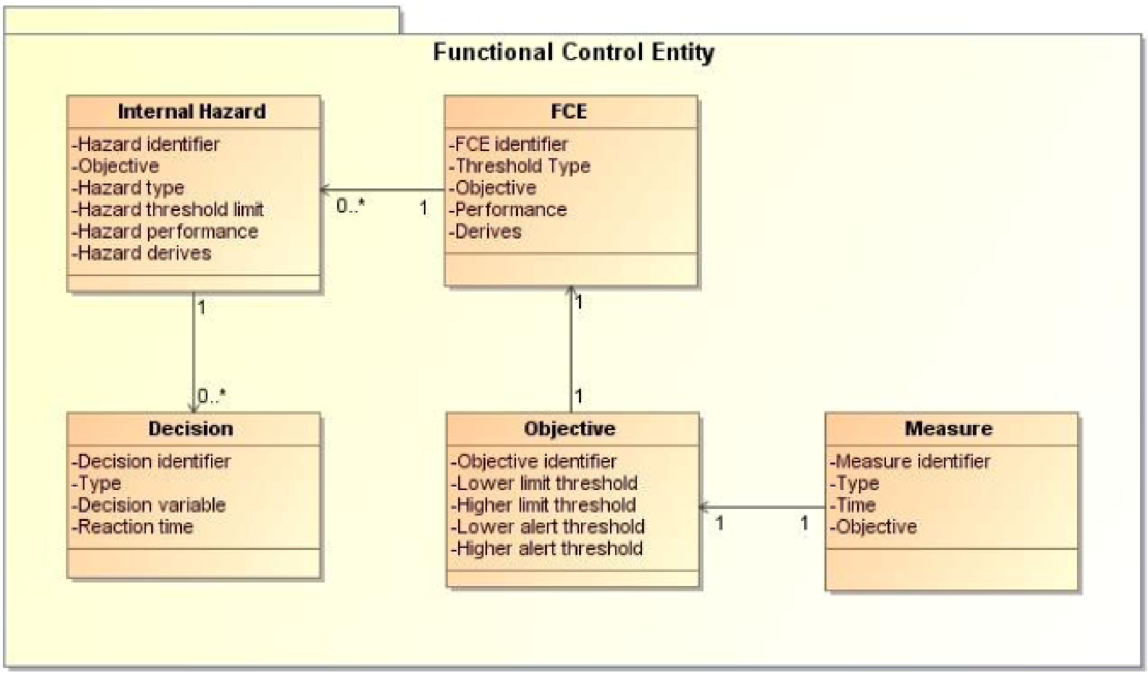


Figure 19 Functional control entity package (see online version for colours)



The decision-making process of the FCE (assessment and decision) is based on the 'IMC' model (Intelligence, Modelling, Choice) (Le Moigne, 1974).

This model shows the close imbrication of the concepts of decision and information, which is important for the study of performance and for designing a system of effective decision.

Generally, a decision-making process consists of restricting a set of possibilities to a strict subset and evaluates this restriction.

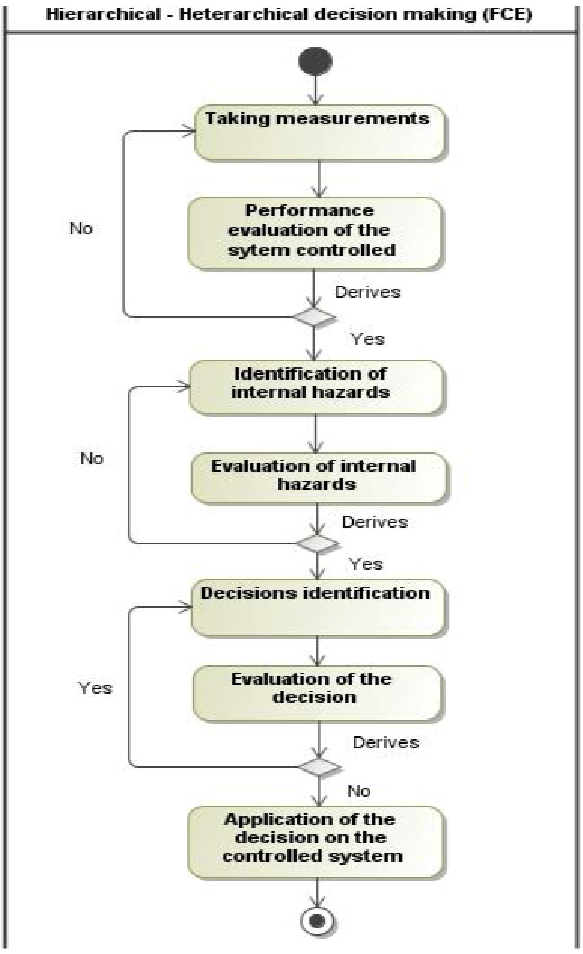
The decision-making process of the FCE (Figure 20) summarises three evaluation stages:

- the evaluation of a controlled system performance
- the evaluating of the hazard in case of derives
- the evaluation of the decision to implement.

3.4.3 The concept of performance indicator

In our modelling approach for the simulation of production systems, characterising the efficiency of the system is one of our priorities. Therefore, we have established performance indicators that correspond to the tools that the control system will use in its decision-making process to evaluate the performance of the controlled system.

Figure 20 Decision making process (FCE) (see online version for colours)



Performance indicators are functions that depend on the values associated with attributes and variables of a resource at any time. The value of an indicator is updated during the time evolution of the state of the resource during simulation (process indicators) and at the end of simulation (performance indicators). The information necessary for the formalisation of these indicators are directly related to the production time.

- *Performance indicator package*

The *performance indicator* package (Figure 21), corresponds to the tools that will be used by the Control Entity to evaluate the performance of the controlled system.

There are three types of performance indicators calculated by the system, which inherit the object class *Performance Indicators*. These are indicators of *Time, Rate* and *Counter*.

- *Synthesis*

The overall package of the control system is given in Figure 22.

4 Industry application

This industry application shows a real case study conducted in a Moroccan factory, with the aim to validate the efficiency of a tool called SIM-PROD that we developed based on the Visual Basic Editor in Arena simulation software (by Rockwell Automation).

The SIM-PROD model is a simulation platform that aims to help the user in the modelling approach for simulation and analysis of manufacturing systems production. This assistance is directly related to our commitment to offer above all a flexible simulation environment, generic and easy to use.

This platform will add a user friendly aspect to Arena making it possible to be used by a simple operator with no previous knowledge or deep comprehension of the modelisation of the production system.

We present this case study into three parts:

- the first part is to analyse the system to be studied to determine the general environment issues and objectives
- the second part is to model the system to be simulated using the proposed methodology
- finally, the third part is to present the simulation results of a post problem to show the advantages of the integration of process control in the simulation.

4.1 Analysis of the system

The studied system is a production system of a Moroccan manufacturing company specialised in the production of valves and electro valves. The production system produces five major families of finished products (Table 1) with an average production of 100,000 valves/year.

Figure 21 Performance indicator package (see online version for colours)

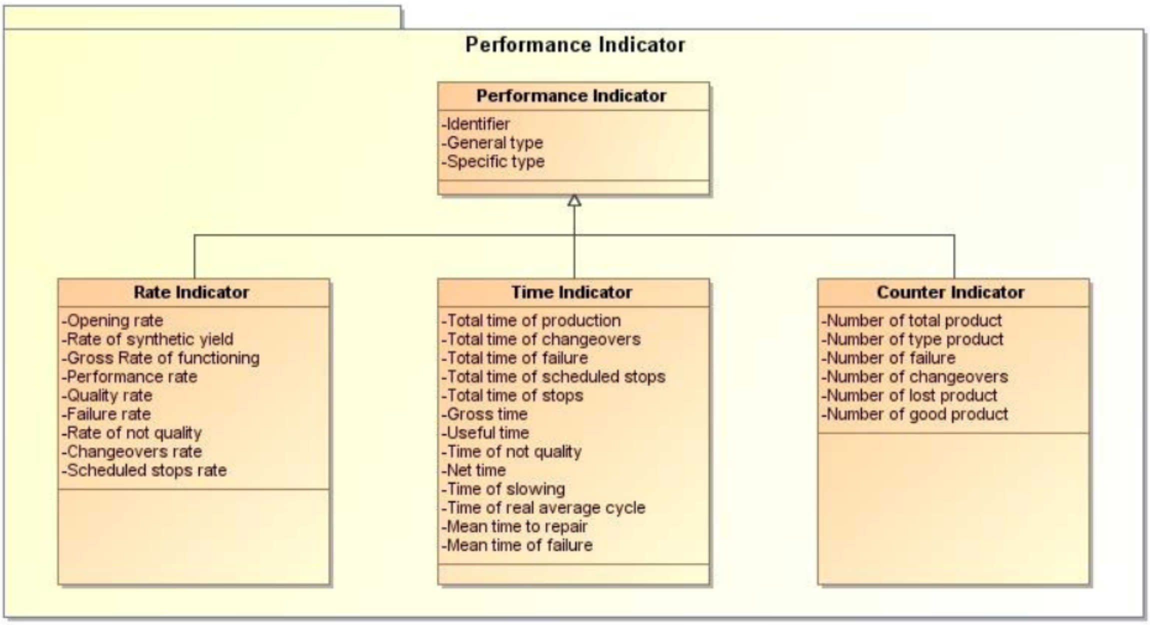


Figure 22 Control system package (see online version for colours)

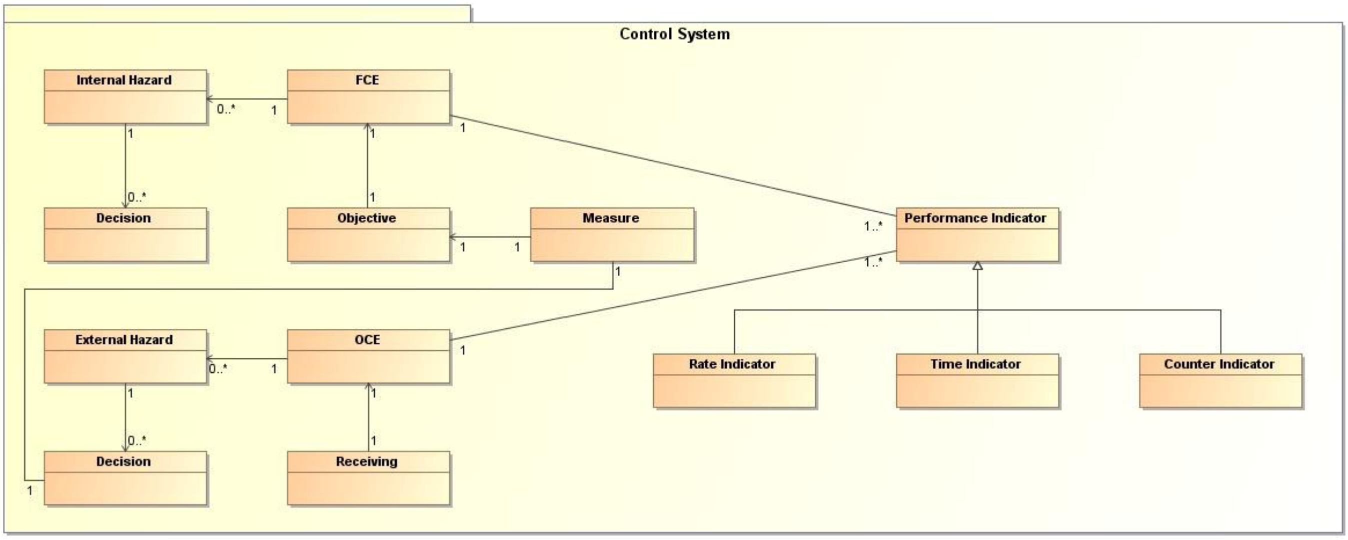


Table 1 References of product families

Product family	*References*
Gate valves	BVP 70C, 70RI, 75HA, 10NE
Butterfly valves	BVP 79G, 79BC, 79MB, 79U, 79BX, 79R
The non-return valves	BVP-08
The ball valves	BVP 16L, 17, 18, 07Y, 19
The Knife Gate valve	BVP 77X, 77AZ, 78HE

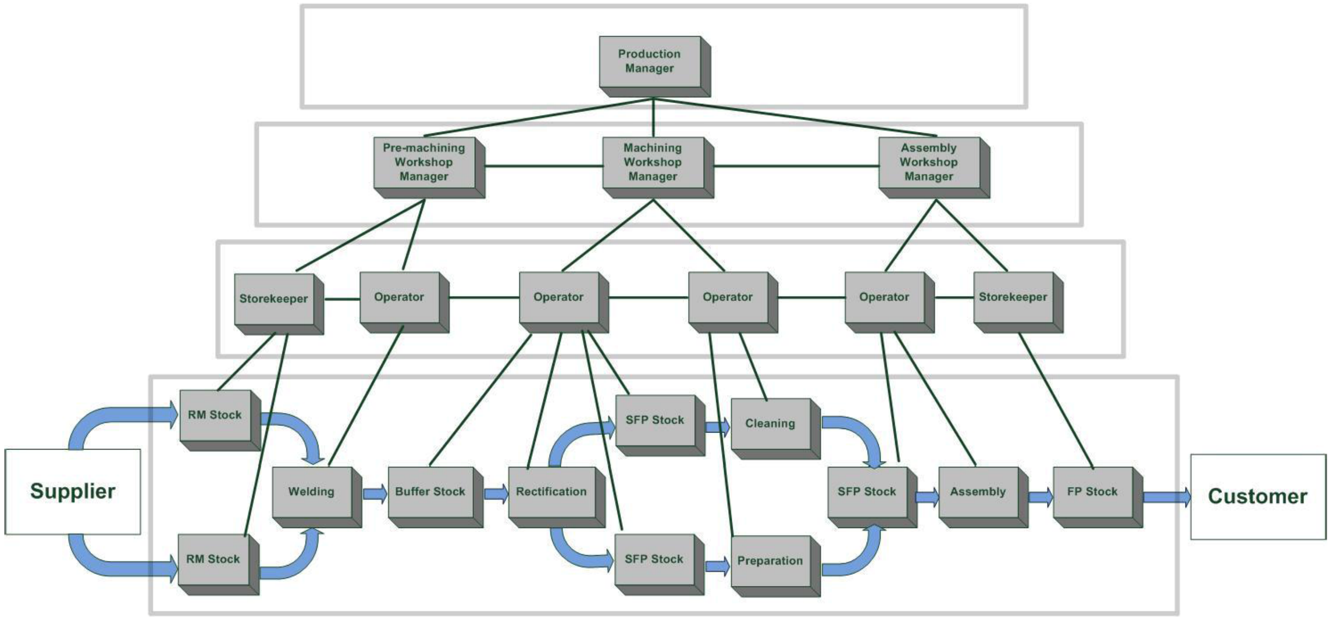
To validate our model, the study will focus more specifically on the main family product of this system which is the Knife Gate valve product. This reference is ~55% of the total production of valves, with an average of 4000 valves manufactured per month. Production (Table 2) is divided as follows:

The production system (Figure 23) is made of five distinct areas: *Receiving*, where raw material is received from the suppliers. *Pre-machining*, where received raw material is treated. *Machining*, where pre-machined parts are treated. *Assembly*, where manufactured parts are assembled. *Expedition*, where pallets of finished product are packed and shipped to customers.

Table 2 Monthly production of knife gate valves

Knife gate valve	*Reference*	*Quantity/ month*	*Manufacturing batches*
Product 1	BVP 77X	1400	350
Product 2	BVP 77AZ	1000	250
Product 3	BVP 78HE	1600	400

Figure 23 Mechanical production workshop (see online version for colours)



The system includes the following resources: two stocks of raw materials, a welding station, a rectification station, a cleaning station, a preparation station, an assembly station, a stock of finished products and other transportation resources responsible for transferring products between positions.

Four operators and two storekeepers are assigned to control these positions. The *first storekeeper* receives the raw material, and manages the two stocks of raw material. The *first operator* manages the welding station. The *second operator* manages the buffer stock, the rectification station and the two downstream stocks of semi-finished products. The *third operator* manages the cleaning station, the preparation station. The *fourth operator* manages the assembly station and the stock of semi-finished products upstream. The *second storekeeper* manages the stock of finished products.

The production system is managed by a production manager. Under his direction are located three managers who oversee the production system workshops: The *pre-machining workshop manager*, the *machining workshop manager, the assembly workshop manager*.

The first storekeeper and the first operator are assigned to the *pre-machining workshop*. The second and third operators are assigned to the *machining workshop*. Finally, the fourth operator and the second storekeeper are assigned to the *assembly workshop*.

4.2 Modelling of the system

To model the system, the proposed methodological approach that breaks down the production system into a physical system and a control system has been applied.

The application of this methodology permitted to analyse the system to be studied and collect the necessary data to constitute the model representing the physical system and its control process.

The *physical system* will be modelled using generic concepts *Resource* and *Product*. Thus, the Resource will represent the positions and will manage their information, through structural, functional information and information indicative of performance.

The *Product* structure represents the physical flow circulating in Resources. It is this structure that will include information related to products. It can be a part, a batch, a manufacturing order, etc.

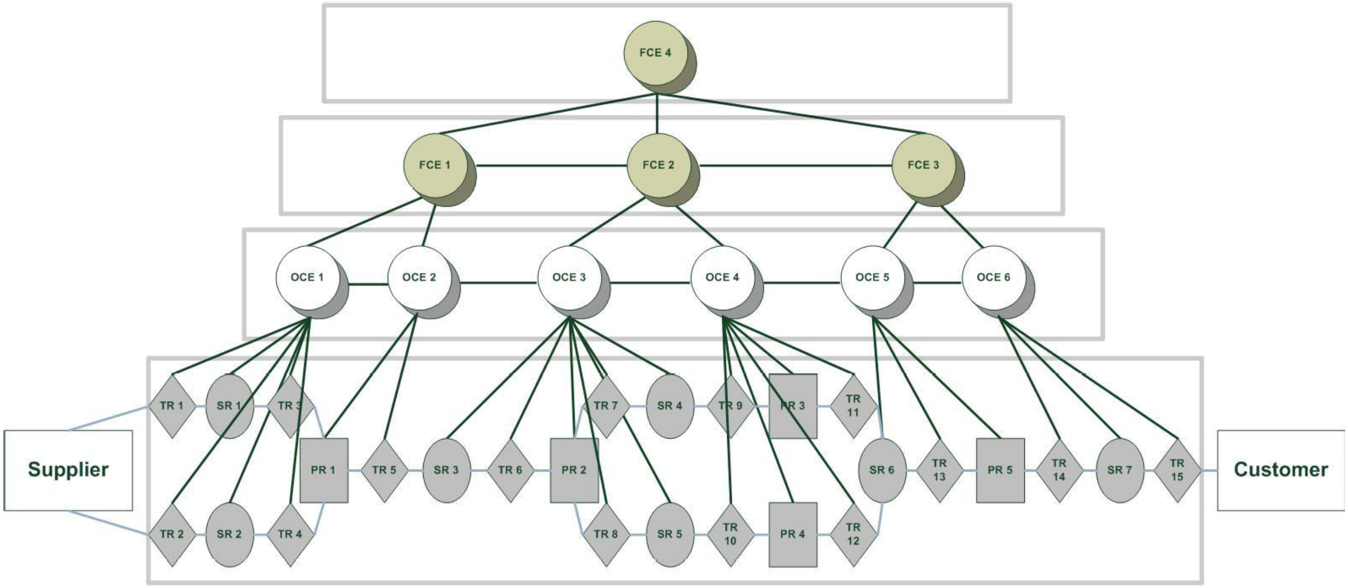
As for the *control system*, represented by all operators, workshop managers and the production manager, it will be modelled by *CE*.

Thus, the physical system is made of various resources and also of parts to be manufactured. And the control system is made of six individuals on a first hierarchical level, of three others on a second level, and of a last on a third level.

The production system mentioned can be modelled by the following (Figure 24):

- *Resources*, in the case of physical system. These resources can be Production Resources *(PR)*, Storage Resources *(SR)* and Transport Resources *(TR)*.
- A *Control Entity (CE)*, in case of control system. These *CE* can be Operational Control Entities *(OCE)* for the first hierarchical level and Functional Control Entities *(FCE)* for the second and third level.

Figure 24 A modelled workshop (see online version for colours)



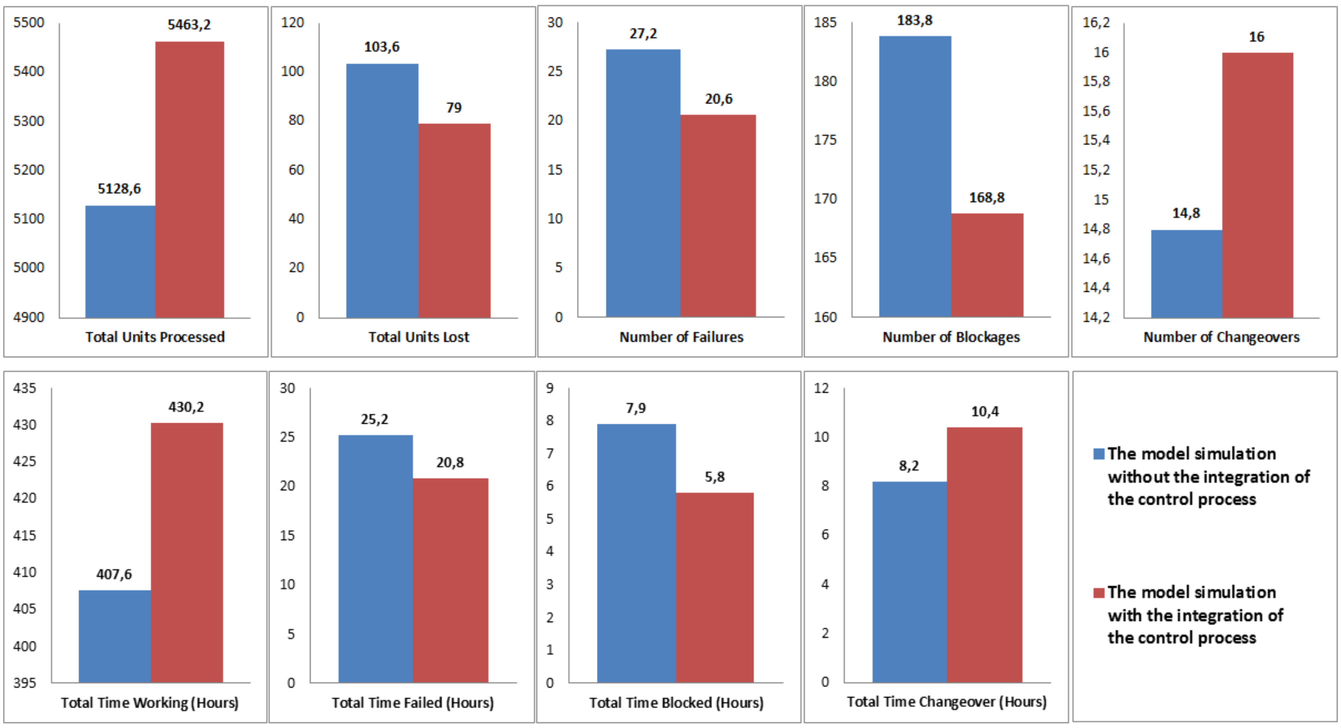
4.3 *Simulation of the system*

The simulation study consists of presenting the results of the simulated model using the platform SIM-PROD that we have developed. As an example, we present the case of a problematic station to show the advantages of the integration of the control process in the simulation.

Following the simulation of the system, it appears that the production encounter various management problems in the machining workshop and more precisely in the *rectification station*. These problems cause a disturbance of the system's productivity. Therefore, the delivery time announced to customers increases and the customer satisfaction rate decreases. To overcome this situation, we integrated control concepts developed in the simulation process to improve the system.

The rectification station represents a bottleneck and its management is a priority in order to avoid blocking the production line. Figure 25 shows the results of simulation of the station with and without integration of control processes.

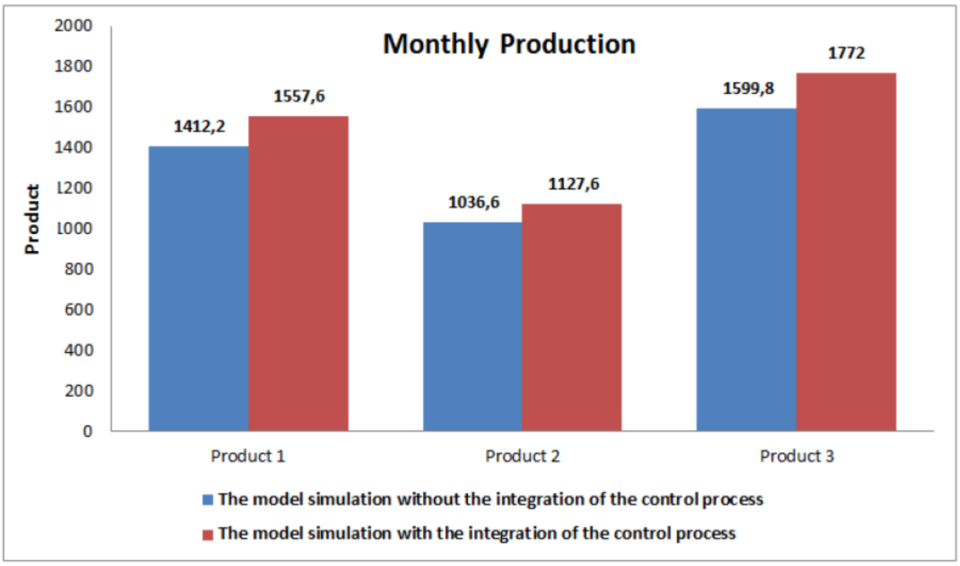
Figure 25 The simulation results of the rectification station (see online version for colours)



By analysing these results, we can deduce that the number of total units processed has improved and the number of total units lost declined. Same for the number of failures and number of blockages which decreased by applying control concepts. Then, by analysing the time indicators, we can deduce that the number of hours of 'Total working time' has increased and the number of hours of 'total time failed' has decreased, same thing for the hours of 'total time blocked' and 'changeovers' who declined.

The integration of the control process has not only helped improve the various station of the production system, but also increased productivity. Every improvement made affects the production of finished products, which we can deduce from Figure 26 where we have a net improvement of about 10% of the monthly production.

Figure 26 The simulation results of the monthly production of the family of knife gate valves (see online version for colours)



5 Conclusion

To better manage production systems, complicated by a constantly changing environment and a fierce competition, the use of a tool for decision aid is becoming essential for the industry. Among these tools, simulation is the most requested technique because of the extent of its field of action, and of its power analysis as well as the diagnostic possibility it offers. However, this technique has still certain limitations due to the complexity of concepts, the lack of methodology for model development, the current difficulty in representing the decision flows (thus the control processes) all of the existing simulation software on the market require a certain knowledge of the user regarding the concept of modelisation.

Thus, generic concepts and methodological approach are proposed to address these gaps. The proposed concepts are based on an approach of hierarchical analysis of the production system, both for the physical process, through the representation of resources, products and their operations, and for the associated control process, through the representation of the OCE, the FCE and the performance indicators. This approach allows the introduction of control in the simulation process to make it more active and so become a real tool for control.

However, the requirement of the modelisation knowledge using a simulation software will be overcome by a suitable simulation platform called SIM-PROD that we are in the process of improving.

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