An Integration Architecture for the Automation of a Continuous Production Complex

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Abstract

The development of integrated automation systems for continuous production plants is a very complicated process. A variety of factors must be taken into account, such as their different components (e.g., Production Units control systems, Planning systems, Financial systems, etc.), the interaction among them, and their different behaviour (continuous or discrete). Moreover, the difficulty of this process is increased by the fact that each component can be viewed in a different way depending on the kind of decisions to be made, and its specific behaviour.

Modeling continuous production complexes as a composition of components, where, in turn, each component may also be a composite, appears to be the simplest and safest way to develop integrated automation systems. In order to provide the most versatile way to develop this kind of system, this work proposes a new approach for designing and building them, where process behaviour, operation conditions and equipment conditions are integrated into a hierarchical automation architecture.

Key words: Hierarchical Automation Systems, Process Automation, Object Oriented Systems, Enterprise Architecture Models, Enterprise Integration

1 Introduction

There is a real need for the integral automation of a Continuous Production Complex (CPC) to improve performance and to give fast and adequate responses to market requirements. The integral automation of these complex plants exhibits many difficulties due to a diverse number of factors that need to be taken into account. Examples of these factors are:

(1) The complexity of modeling production processes (physical modeling) within the Production Units (PUs),
(2) The interrelation among PUs,
(3) The use of different automation technologies based on the specific processing requirements of the PUs,
(4) The geographical distribution of the production process, and
(5) The changes of raw materials (inputs) and processes operational conditions (infrastructure, faults, failures, etc.).

The need of an integrated view of an enterprise is a well-known aspect in automation. In order to maintain their markets, enterprises must ensure fast responses to internal and external changes. An enterprise must be *efficient* and *responsive*. It must ensure *better quality products* and accomplish the *specific needs of the customers* [1].

Despite the fact that the automation process depends on the characteristics of a particular enterprise, its necessity is common for all types of enterprises. Automation is usually classified based on the type of enterprise into the following categories or classes: automation for manufacturing systems, automation for batch systems and automation for CPCs.

The integration of the automation for manufacturing systems has been widely studied in the literature as Computer Integrated Manufacturing (CIM). This is a well-established area for which several models have been developed during the last decade. Examples of these models are the CIMOSA approach [2–6], the GRAI model [7] and the PURDUE Enterprise Reference Architecture (PERA) [8]. An approach to achieve the integration in process industries called Computer Integrated Processing (CIP) is given in [9] and is based on the Y-

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Model developed for CIM [10]. Our approach is continuous production process-oriented. It borrows and adapts several concepts from PERA [8], CIMOSA [2,3] and PROSA [11], which are mainly devoted to manufacturing systems and uses a new perspective to understand and model the enterprise as a whole.

In this paper, we apply the CIP approach to CPCs by generalizing the Y Model. CPCs can be viewed as a set of PUs that shares resources (e.g., energy and raw materials). PUs can produce the same output (i.e., product) as shown in figure 1.a. They can also be linked in order to perform a more complicated process, as shown in figure 1.b. The second production structure represents a complex system [9]. Then, a complex system for continuous production is composed of several semi-autonomous subsystems, which transform inputs into intermediate or final outputs (i.e., products). An autonomous system is defined here as in the Antsakils - Passino work [12]

Classical examples of CPCs are oil and gas production systems, refineries, petrochemical plants, energy generation systems and some distribution systems (e.g. electrical, gas and water). For oil and gas production systems, the process starts with the oil extraction, and there are specialized PUs that generate intermediate products, such as crude oil and gas separation, which are inputs to other processes that treat those products for further processing or for final uses. Structures of this type are called complex production structures (see figure 1.b).

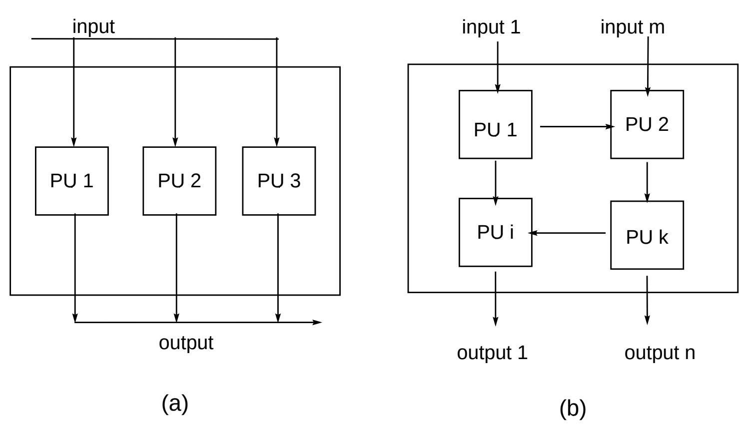

Fig. 1. Single Production Structure vs. Complex Production Structure

This paper is organized in six sections including this one. Section 2 describes different approaches for enterprise modeling. In section 3, we describe an integration model for continuous production complexes. In section 4 is proposed an integration architecture. An application of the integration model and its architecture to the automation of a small water treatment system is described in section 5. Finally some conclusions are given in section 6

2 Enterprise Modeling Approaches

In this section, a description of three different modeling approaches or views that are used to model an enterprise is presented. The first one deals with organizational aspects; the second view models the enterprise using the relationships among its components; and the third one is based on the information flows. In this work, we propose an enterprise model that also includes a decision-making schema. There three, different views will be merged in order to obtain an integrated model that represents the enterprise from a more comprehensive perspective that includes the way enterprise decisions are made.

2.1 The Hierarchical Approach

As discussed in the introduction, a CPC is composed of several autonomous PUs, which internally control their own behaviour in order to accomplish their goals. The whole system achieves its goals, by assigning simpler goals to each PU. If a PU has several subsystems, the optimum for that PU is established in the same hierarchical way. Then, the organizational architecture for the CPC can be structured into layers, similar to the CIM model. This architecture, shown in figure 2, comprises four levels:

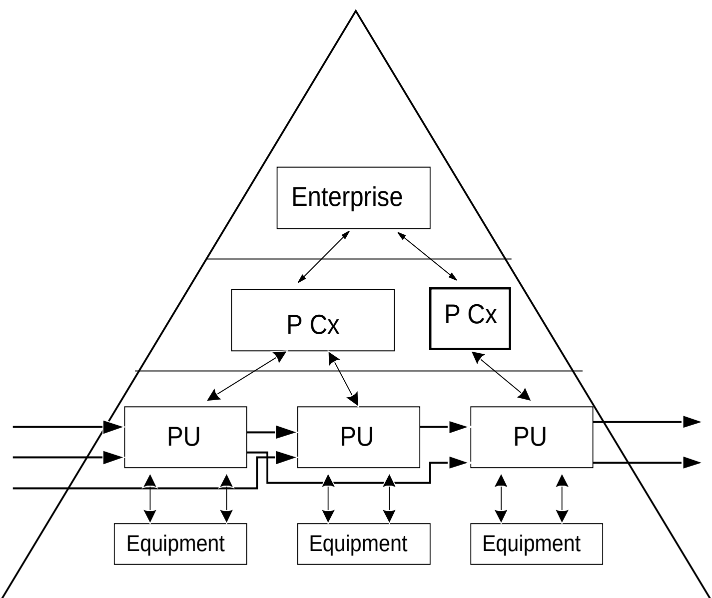

Fig. 2. The Enterprise Organizational Architecture

(1) **Enterprise level**. At this level, the *strategic planning function* and the centralized management of the enterprise, which decides about the policies for Finance, Human Resources, Marketing, Research and Developing

activities, are performed. These activities deal with the establishment of long term plans and enterprise policies. In certain cases, some operational and support activities are centralized at the enterprise headquarters.

The enterprise level coordinates the production activities performed at the Production Complex (PCx). In some cases, a plant is a Production Complex and the association of many plants conforms a topology that allows to ensure enterprise's goals.

(2) **Production Complex level**. This level is oriented to coordinate the PUs that belong to a production complex (PCx), with the purpose of optimizing the resources and scheduling the operations. Production Complex Management establishes production quantities, sends posting orders, performs accounting functions and establishes material requirements. Process simulators for performance evaluation and personnel training are needed to operate PUs. To carry out these activities, process variables obtained from PUs must be appropriately stored. A PCx may have several PUs, which can produce the same type of product or form a production line. Intermediary and final stocking systems are part of the PCx and can be considered as PUs. Maintenance activities are managed at this level of the enterprise.

(3) **Production Unit level**. At this level, PUs perform the production process of one kind of product at the same time. A PU that performs both control and regulation functions and "knows" how to achieve its production goals and the state of its production, may be interpreted as a semi-autonomous unit. PUs may be composed of one or more equipment units, which perform the transformation processes.

These transformation processes can be physical and/or chemical. The equipment may have control stations that perform control actions in the physical process. PUs must know about their internal capabilities, states and restrictions. The PCx may align the PUs in such a way that they perform different production processes or change the production level based upon enterprise requirements or the internal state of the PUs.

(4) **Equipment level**. The production infrastructure as well as the devices where processes take place and the necessary instrumentation to link up the measurement and regulation of the processes are located at this level. There are also, control devices and networks that are in charge of controlling the process and obtaining performance information about the infrastructure. Control devices perform regulatory and sequential control actions for the processes.

The PU is the central transformation unit of the organizational architecture of a CPC and may also be interpreted as composed of several PUs. Both an enterprise and a PCx can also be seen as PUs.

The Object Model that represents the global architecture of the enterprise is shown in figure 3. This model is described by means of a class diagram using the Unified Modeling Language (UML), a de-facto standard for system and software modeling. Complete details on this notation can be found in [13] and [14]

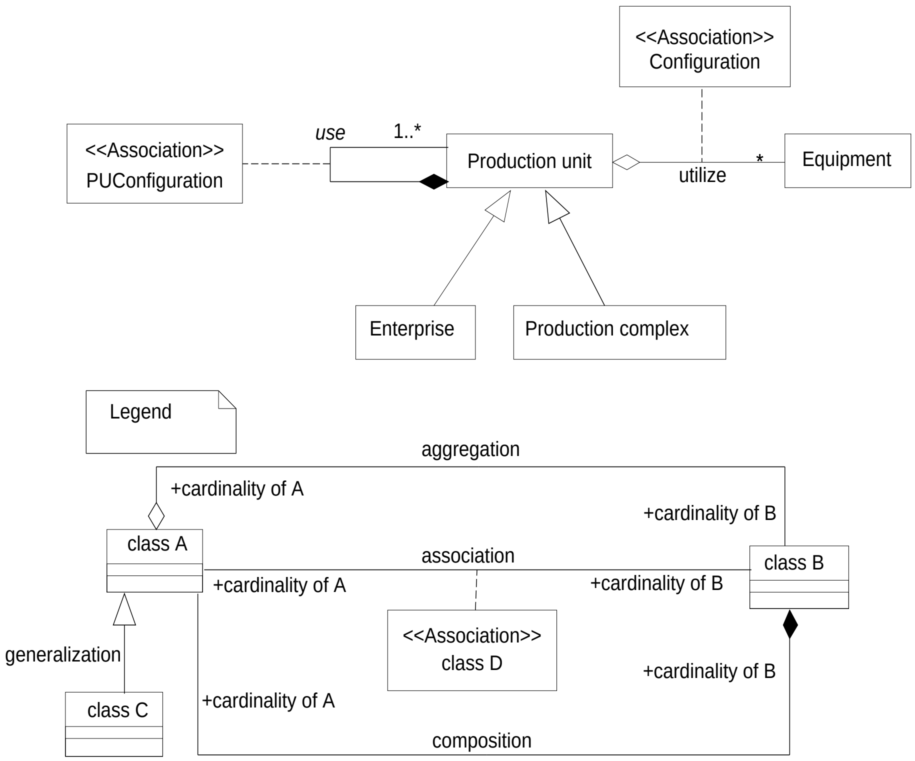

Fig. 3. An Object Model of the Enterprise Architecture

2.2 The Holonic Approach

A PU is composed of a set of elementary units (equipments), which are organized in such a way that allows performing transformation processes (chemical, physical, transport, etc.). It aims at obtaining requested products with a good performance. In [11,15], three modeling elements are proposed for manufacturing systems based on the holon concept. These elements are order holon, product holon and resource holon. In the context of this work, the following three elements are used to describe CPCs: Production resources holon, Mission - Products holon and Engineering holon.

- **Production resources**. The following list represents key elements in the operation of a process:

(1) material resources, that form part of the productive infrastructure,
(2) production material and
(3) energy for the execution of the process.

Examples of resources are:

    - *Production infrastructure.* This resource is associated with the mechanical, electrical, and other elements, where the transformation functions, mixture, and/or material transport are performed. All of them consume energy to perform the production task. The infrastructure has a nominal capacity associated with its own design, and a real capacity depending on the aging or degradation occurred throughout time. The infrastructure may be in one of the following states: available, in production, in maintenance and out-of-service.
    - *Production Materials.* This resource is related to the materials to be processed at each point of time. Materials have a certain quality that influence the processing capacity. The production material may be measure in terms of existent volume or using a rate of arrival in units per period of time.
    - *Personnel.* Associated with the production, it is also required to know the capacity and availability of human resources for the execution of control tasks, supervision, measurement, planning, etc.
    - *Services.* Other resources are energy, refrigeration, raw water, disposal treats, which are also needed in the production process.
- **Mission - Products**. Each PU encompasses a set of products obtained by using resources and production methods. The mission of a PU is to obtain a set of products within a predefined time. There is a set of predefined objectives for each PU, whose evaluation may be assessed. The product is associated with a production order, which can be in one of these states: waiting, in execution, or finished. In the case of continuous production processes, the product is associated with production objectives, measured in terms of amounts by time unit. For a specific product, its quality is measured according to given specifications.
- **Engineering**. A product is developed using resources and following a specific production method. There is an optimal method to accomplish a production task which depends upon the available resources (condition of the infrastructure, quality of the production material, etc), to fulfill predefined specifications of the products. This method may vary in time, whenever changes in production materials, equipment or in the specifications of the product take place.

  Engineering systems must be able to handle the following activities:
    - Establish and evaluate different production methods,
    - Determine PUs capabilities and capacities and,
    - Evaluate the performance of a PU.

The dynamics of a PU may be represented by means of a transition system such as Petri Nets or Finite State Machines. The behaviour of such systems can be described in terms of Discrete Event Dynamic Systems (DES). In this way it is possible to follow resources or missions changes and, from the point of view of engineering, to select new recommendations for production goals. The relationships among the three elements of a PU are shown in figure 4.

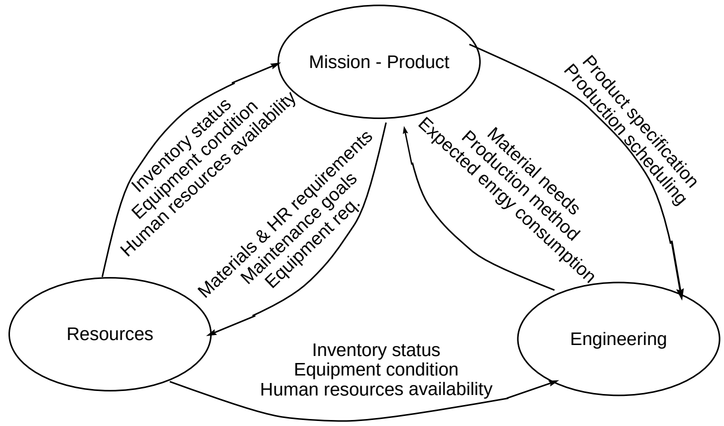

Fig. 4. Relations among elements (holons) within a PU

2.3 The Enterprise Business Model Approach (3D-EBM)

According to the hierarchical vision approach described in subsection 2.1, the information regarding the different activities performed in the enterprise must flow through the hierarchical organization. This model keeps the organization hierarchy and considers the holon model to make decisions. The availability and certainty of the information, regarding the process, is very important to accomplish the decision-making tasks. The information may be either engineering information or resources information as explained in [9]. In this paper, the model shown in fig. 5, named 3-Dimensional Enterprise Business Model (3D-EBM), which describes the information flow in the enterprise is proposed. This model is described in terms of axes and planes.

The 3D-EBM describes the functions performed by the enterprise as follows:

2.3.1 Axes Description

- The x-axis corresponds to the support-area functions. These functions manage economical resources as well as accounting functions for a process.
- The y-axis identifies the plant PUs, the relations among them, and the topological PUs structure which allows the execution of all production tasks. PUs hierarchy must be described over this axis. This axis is related to the value chain obtained by the product when it passes through the PU.
- The z-axis corresponds to the decision activities that happen within the enterprise. Planning and scheduling activities are modeled over this axis according to the hierarchy and functional decomposition. PUs perform the assigned tasks established by the decision axis. A decision may be automatic in the bottom levels and semiautomatic (or with automatic support) in the high decision levels.

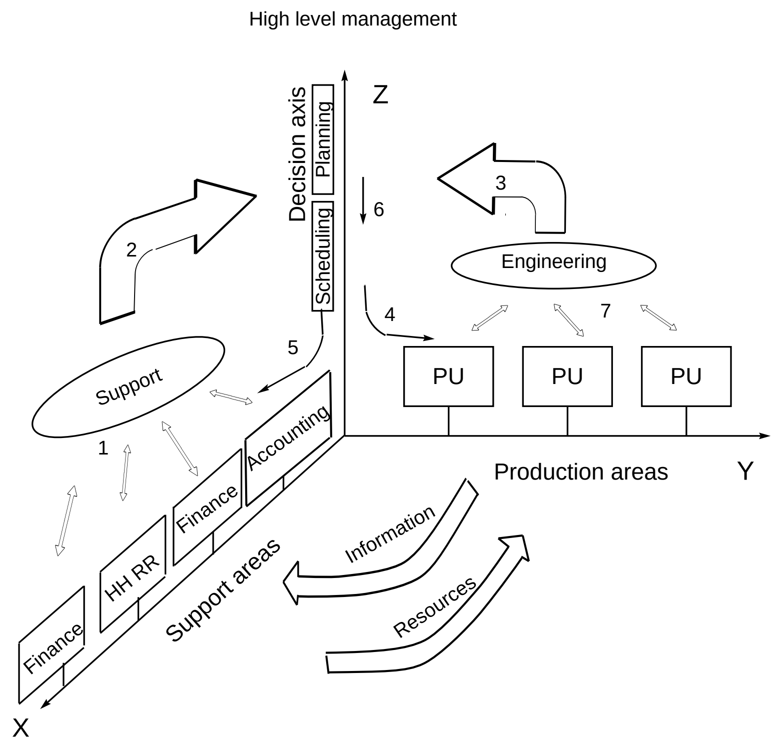

Fig. 5. Three axes organization

2.3.2 Planes Description

- **Plane z-y** describes the interaction among the capabilities of the PUs *y-axis* and the decision systems *z-axis*. It provides information about the state of the PUs and helps in the evaluation of the performance of the PUs. That is why it is referred as the engineering plane.
- **Plane x-z** establishes the link among the support *x-axis* and the decision systems. It helps to the economical analysis of the PUs and provides information about budget availability and financial resources.
- **Plane x-y** refers to the way the support systems and the PUs exchange resources and production information.

A detailed description of the information flow through the enterprise is included in the appendix A given at the end of the paper.

3 An Integration Model for PUs

In order to integrate the automation systems for CPCs, it is necessary to have a model for a PU. Apart from the PU behaviour, this model must describe the vertical integration of PUs into PCXs. It is important to remember that the PCXs and the enterprise itself may be considered as a PU.

The PU is described as an autonomous system in the same way it is defined in [12]. According to this view, a PU is able to take internal decisions regarding its mission such as: change the procedure to make its products, detect if one of its goals have been changed, and inform if the changed goal can be accepted. It must also, informs when a goal is accomplished or if it can not be reached due to PU failures. Raw material, energy & services and information are PU inputs, whereas products, information and waste are PU outputs, as illustrated in figure 6.

Two principal elements coexist in a PU. They are physical elements (e.g., mechanical, electrical, etc.) and/or chemical processes that transform input materials into other products. Based upon the PU knowledge, the information and decision systems allow the control and regulation of the processes. They also exchange information with other systems in order to have the overall control and regulation of the complex.

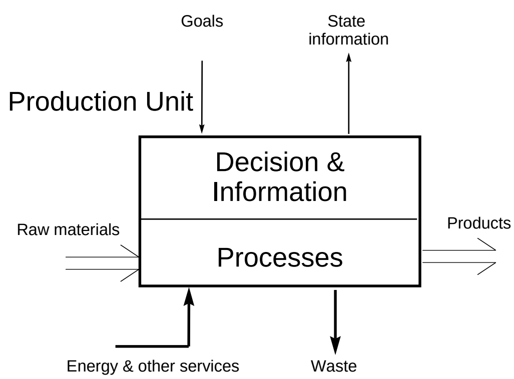

Fig. 6. Inputs - Outputs in a PU

3.1.1 The Decision Making Cycle (DMC)

The mission of the DMC is to ensure a proper process behaviour by maintaining a continuous process evaluation based on the comparison between the process state and the assigned missions. This DMC is shown in figure 7. The main activities of this cycle are explained next.

- **To sense**. This task corresponds to the measurement of the more significant variables of the process. These measurements are obtained by means of sensors that are located in the processes. Sensors can operate directly with the physical processes or over a database containing process values.
- **To observe**. The process observation generates information about processes states. This task includes the following activities: generation of new variables by fusion of measured variables and transformation of significant variables

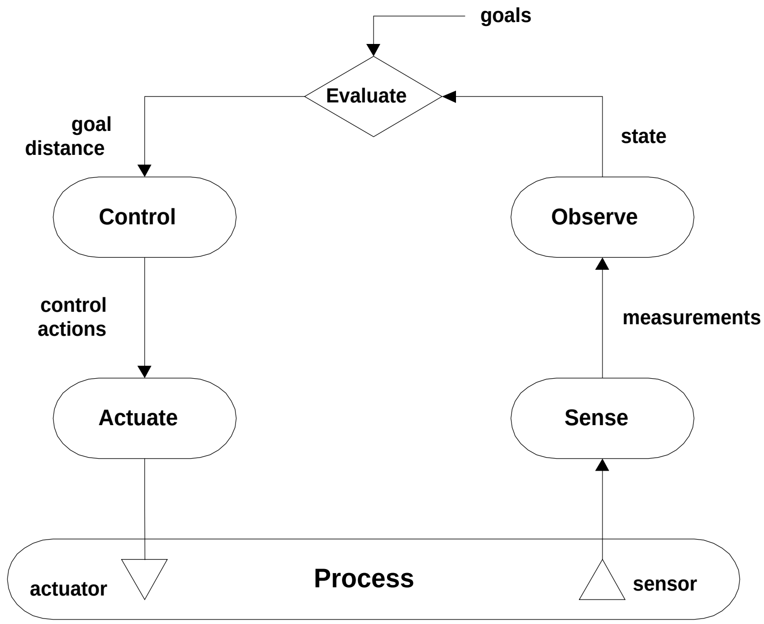

Fig. 7. The decision making cycle (DMC)

of the processes in process state variables (discrete or continuous). This task is equivalent to determine the state of the process. A complete PU is composed of several interconnected processes.

- **To evaluate**. It involves the analysis of the information about the process state and its comparison with the mission assigned to the process. Normally, this task is done in different scenarios indicating the process failures that might take the process state away from the assigned mission.
- **To control**. It is concerned with the evaluation of objectives to be accomplished by the process. These objectives determine the mission of the PU. This may be accomplished by evaluating different scenarios and their optimization (i.e., the selection of one of different alternatives and specification of new goals).
- **To actuate** The final step in the DMC takes into account the internal characteristics of each one of the controlled / supervised processes. The calculated actions must be transformed into recommendations for each one of the sub-processes that take place inside the PU. These recommendations are distributed on time as a sequence of steps for the corresponding sub-processes.

3.1.2 Characteristics of the DMC within each Level

The characteristics of the DMC depend on the functions performed in each level of the enterprise organizational architecture. According to the figure 2, the principal decision functions performed at each level are described as follows:

- **Enterprise**. At a global level, the enterprise must take into account some general indicators that allow to evaluate the performance of the global system, and establish its position regarding market, concurrence and geographical location. Indicators must be obtained through the information systems considering measurement elements to evaluate: financial state, product quality, consumers satisfaction and acceptance, capability, capacity, condition and performance of the production units and existence of raw materials and products. Analytical packages help the managers to evaluate the enterprise condition in order to obtain those indicators that may be considered as variables of the enterprise state. The mission of the enterprise, which is defined by the enterprise managers, is compared with the state of the enterprise, in order to define the enterprise policies. The time to perform the mission evaluation and state determination depends on the manager's experience. The automated system must support the recovery of data from the PU information systems, and the execution of applications for the evaluation of activities. In the same way, the establishment of *control activities* (policies, missions, etc.) must be supported by simulators and converted into missions for the PUs.
- **Production Complex**. In a PCx, several production units operate in a coordinate way in order to obtain finished goods. The internal mission establishment for each PUs is defined by taking into account the mission for the complex and the available resources: *PUs operational status*, input materials and possible flows of products. The operational status of a PU is given by its capacity (committed and real) for a scheduled time (production resources). The definition of the mission for each PU considers economical aspects which are taken into account in order to optimize time. Among these aspects are production costs of the PU, value of the inputs and value of intermediate and final products.

  The applications that support this type of decisions, are generally started manually, and the decision maker is an specialized operator that indicates which one of the applications must be started for each one of the tasks belonging to the DMC.
- **Production Unit**. In a PU, the decisions are more structured, and the DMC can be more automatic, than in the other levels. In accordance to the model shown in subsection 2.1, there are two kinds of PUs: the simplest PU, that is composed of equipment which can not be separated, and PU composed of other PUs. In the last case, the coordination among the PUs to accomplish an established global mission is its essential task. The principal aim is to ensure the mission accomplishment by changing the PU topology (product flows) or changing the PU production levels while maintaining its restrictions. This type of decisions must be accomplished in real time, and therefore the DMC must be implemented to operate automatically.

  For the simplest PU, which usually involves final equipments, the DMC operates automatically. The DMC deals with real time information and control activities. The controlled processes are physical or chemical, which involve functions like material transport and material transformation, chemical reactions, energy generation, etc. Physical components, such as vessels, reactors, transporting belts, etc., must be commanded in order to obtain products. The functions of the Human supervisors are to evaluate the behaviour of the controlled system by establishing parameters or set points. The supervision task also may be performed automatically or use real time support systems that help the human supervisors.

The DMC can operate in several ways: automatic, such as most systems at the control level; manually, where operators can perform DMC activities using the knowledge that they have about the processes under supervision; or using applications that supports the Decision Making Procedures (DMP).

For manual and supported cycles, systems must provide interfaces that allows the operators to perform such activities.

3.1.3 Modeling PUs Activities

The set of enterprise activities must operate coherently and the information must flow over all planes throughout the hierarchy of the 3D-EBM. Knowledge about PUs, PCXs and Enterprise levels must be stored, processed and transferred by the information and communication technological infrastructure. Decision making activities take into account the information generated by the engineering plane and the economical restrictions represented in the economical plane. The production model described in section 2 for a PU must be generalized for PCXs and plants in accordance with the hierarchical organization. The three-axis model satisfies the information exchange needs of an enterprise, a plant, a PCx or a PU, but it must be customized for each level. The decision-making activities are more on the control domain for a PU than for an enterprise where they are dedicated to long term activities. The fusion between the two models mentioned above is crucial for the elaboration of the Activities Integration model described next.

The description of a PU is given in terms of internal and external objects that can introduce changes on the mission (or new missions). The internal objects within a PU are the following:

- **Product type**.
  The list of finished goods that can be obtained by a process within the production unit following a production method.
- **Production method**.
  Associated with each product type, there is one or more production methods that depends upon the raw material, product amount and equipment conditions. The production method can establish a different usage of the equipment.

- **Mission.**

  For a product class, the PU has zero or more production compromises. A product class can be obtained from one or more PUs. The mission is related to the production to be performed within a time period. To perform that mission, the operation of the PU must be divided into a set of tasks to be performed by the technical infrastructure (equipment or more elemental PU). Those tasks must be scheduled over the infrastructure.
- **Production capability.**

  Production capability is the highest output rate, which could be achieved for a product type in ideal conditions. This production capability may be different if there are changes in the condition of raw materials, plant, equipment, and the personnel capacitation. There are two types of Production capabilities:
  - *Available capability.* The portion of the production capability that can be attained but is not committed to current or future production.
  - *Committed capability.* The portion of the production capability that is currently in use or is scheduled for use.
- **Equipment condition.**

  A PU is composed of one or more equipment (infrastructure) that performs the physical and/or chemical transformations of raw material to elaborate a product. Changes in the equipment conditions result in a new available capability for the plant.
- **Process state.**

  The evolution of the process to commit a given product type results from the composition of the production capability, the state of the equipment (real capability), and the mission achievement (development of a production specification) under a production method.

An object oriented model that represents the components and activities of a PU is shown in figure 8.

The class *ProductionUnit* describes the properties and the behaviour of each PU of the system. This class is an aggregate of products, missions and capabilities that are supported by the corresponding classes: *Product*, *PUMission*, and *PUCapability*. The relationships between the *ProductionUnit* class and their aggregated classes are as follows: a PU produces one or many products, a PU reaches one or many missions and a PU attains one or many capabilities. Also, a PU may have their own equipment, which is a kind of resources.

For each product elaborated by a PU, there are one or many associated production methods, which are represented by the *ProductionMethod* class. The process to make a product by following a production method is stored in the *Process* class, and the association among these classes indicates that a process follows a production method to make a product, utilizing some resources configuration, normally imposed by the selected production method. *Config-*

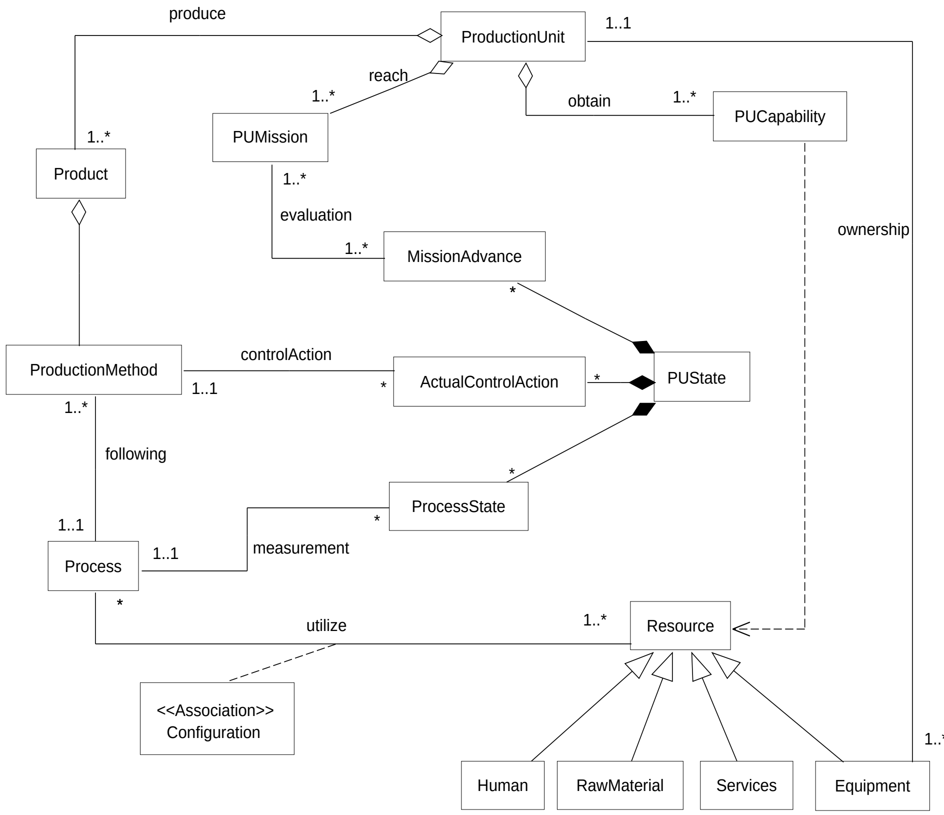

Fig. 8. Class diagram of the PUs Components

uration is an association class that captures the structure and behaviour of the interaction between processes and resources. Figure 8 also categorizes resources as raw material, human resources, resources of service, and equipment, which are supported by the corresponding classes: *RawMaterial*, *Personnel*, *Service*, and *Equipment*. All of them have different configurations depending on the process, which at the same time depends on the production method being followed.

The DMC model as well as the associations *measurement, evaluation* and *controlAction* belong to the *PUState* class. Sensors and observers are used to measure and to estimate the state of a process that follows a determined production method. The *measurement* association performs this task. The comparison between the production unit's state and its mission is supported by the *evaluation* association, and finally, the actuators are supported by the *controlAction* association.

External factors, due to inputs modifications, that influence the PU functionality are the following:

- **Changes in production goals**. A new mission, or an adjustment on an established mission, implies an evaluation of the state of the PU. The consequence of this change is to change the production method by rescheduling the internal activities in order to accomplish the new mission.

- **Changes in physical inputs**. The quality of the raw material can change over the processing time. If those changes are informed by means of a new mission, the PU does not perform any detection activities. But if there are not informed changes, the PU must detect these changes in order to make the internal adjustments to the processes.
- **Changes in availability of other PU**. Failures or changes in the availability of energy, storing and transporting systems that affect inputs, outputs or processing capabilities of the PU must be taken into account by the decision-making systems.

The PU can also affect the environment due to changes in products and/or waste. Those unexpected changes are informed by the process state. A more general class diagram which includes all of the resources utilized in a PU is shown in figure 9. This figure also presents the corresponding sequence diagram, which represents the objects interaction as explained before.

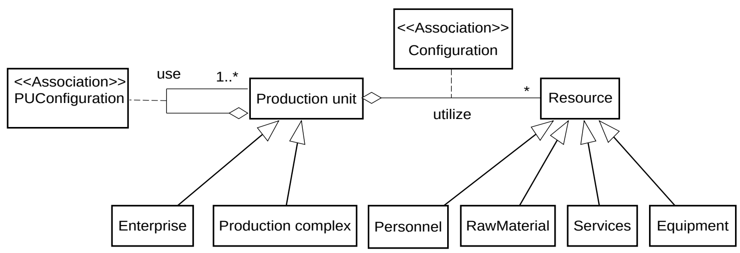

Fig. 9. An extended Object Model of the Enterprise Architecture

3.1.4 Modeling the Objects Behaviour

The evolution of each one of the PUs components describe the global behaviour of the PUs process. Failures inside the process are associated with failures on the equipment condition, and errors on the production method. The behaviour of the process can be described as a Discrete Event Dynamical System.

External factors such as failures on the raw material, a new mission, lack of services (e.g. energy, water, refrigeration, etc.) have influences on the process and may change the PUs mission.

All these elements' behaviour may be described by a set of predicates for each component and for the external factors. The system evolution results in a new state, which is represented as a change on the set of predicates that describes the plant.

Predicates must be stored and modified by evaluation and control applications (i.e., observers and sensors for evaluation, and controllers, optimizers, and actuators for control) according to the mission of the PU.

3.2 The Vertical Integration

Subsection 2.1 included the hierarchical architecture description for the CPC. The DMC must have information about the internal processes using sensors located along the processes. Similarly, the processes behaviour is controlled by corresponding actuators properly located. At lower level, where the simplest PU is located, processes take place on the equipment, and they are sensed and modified by physical devices. For composite PUs, PCXs and enterprises, the controlled processes occur over a logical equipment and therefore the process values are obtained and modified over the PUState and PUMission respectively.

3.3 Integration of the Processing and Control Equipment for a PU

Figure 10 shows the main components inside a PU and their relationship. These components are the Decision System Component which is concerned with the information and systems needed to take decisions, the Control Mechanisms Component which groups all the elements needed to control the PU, and the Production Mechanisms Component which comprises the process, its production methods and the resources required in the production process.

4 The Integration Model: Enterprise + Automation Technologies

The previous section presented a description of the decision-making activities and the way the DMC performs its operations. It is now necessary to take into account the existence of software packages that perform the evaluation and control activities related to the DMP. These software packages allow to transform the information in terms of economical or engineering indicators, as shown in sub-section 2.3. The knowledge about resources (i.e. material inputs, infrastructure and equipment) that informs about the capability and capacity of the PU, is managed by those packages. In the same way, information about the economical indicators, budget, costs accounting, assets control, etc. is managed by other specialized software packages. The architecture of software packages and the knowledge about resources and infrastructure must be handled in such a way that the DMP, distributed on the hierarchy, performs its functions. In order to perform those activities, it is required to have a good matching among the application architecture and the computers and

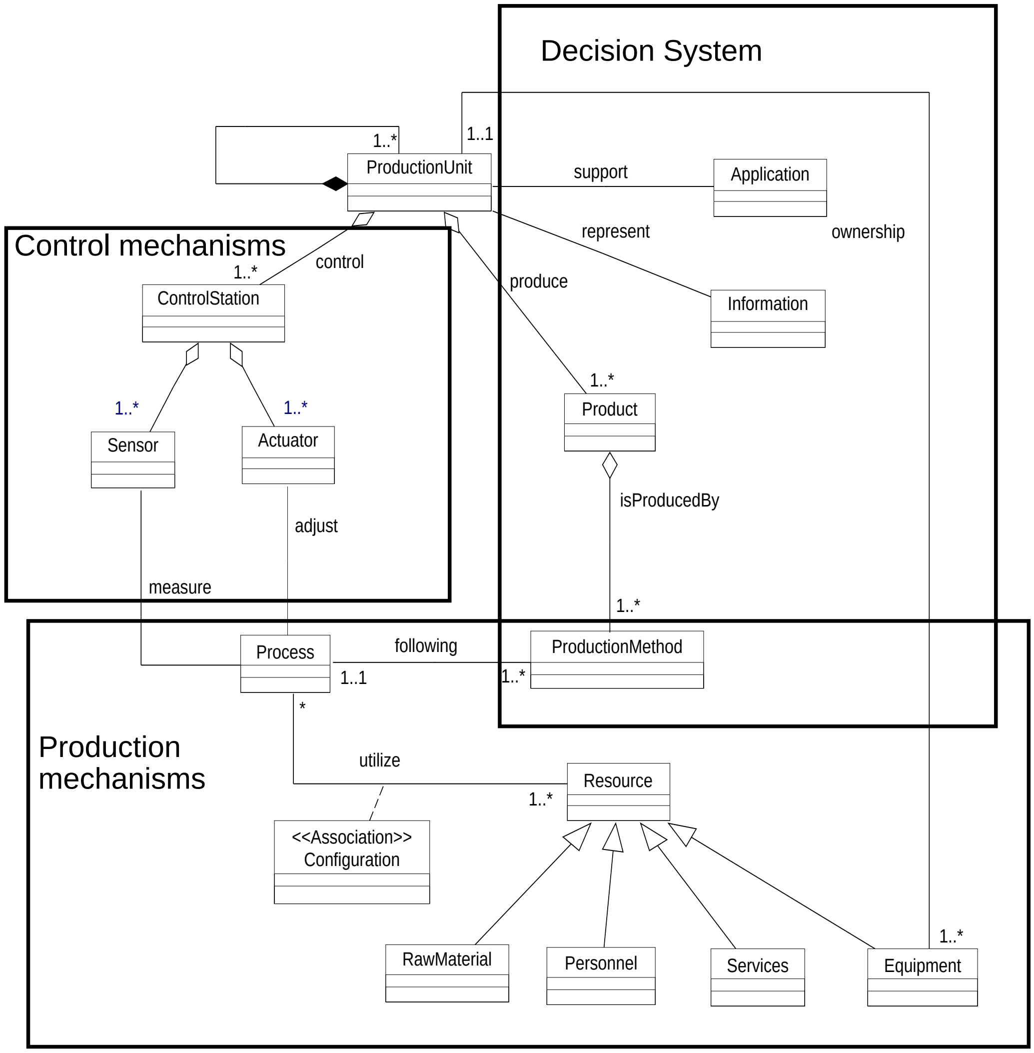

Fig. 10. Technical components in a PU

networks architecture that supports the applications, handles the knowledge about resources and economical aspects and supports the DMP. The proposed integration model matches the links among all elements that conform the automation pyramid shown in figure 11. A brief description of each one of the pyramid faces is given next.

- **Decision making hierarchy**.
  This is the most important face of the integration pyramid. This face was described in section 3 and it is associated with an organization based upon the enterprise functional architecture required to accomplish its mission. The enterprise configuration required to accomplish its mission is obtained using the decision support systems.
- **Resources**. It was mentioned that the production means are the production equipment, input material, and human resources needed to develop or support the production activities. Resources have a dynamics that can not

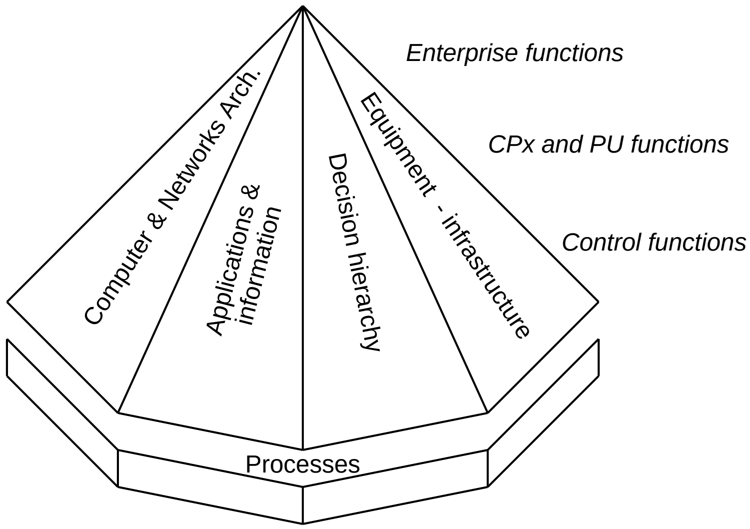

Fig. 11. The Automation Pyramid

be evaluated directly by the decision support systems. Therefore, it is necessary to have specialized units (human resources and software packages) that manage those resources.

- **Applications**. In the evolution of the automation process, enterprises have developed or acquired specialized software packages to support the information management. These specialized software packages are parts of the enterprise and must be integrated to the automation architecture. Enterprise Resources Planning (ERP) and Manufacturing Execution Systems (MES) contain information about resources and financial aspects. In some cases, those software packages are already integrated and have the facilities to perform the information exchange. In other cases, the integration process must create software envelops (wrappers) that allow its integration.
- **Computer & networks architecture**. The information storage and transfer, the execution of applications, and the supporting of decision making models need this face containing network architecture, computers, and information systems. All of them must be adequately utilized depending on the level of use inside the production process.

A class diagram for the automation pyramid is given in figure 12. It shows different kinds of applications used for supporting all of the PU activities. The *Application* class generalizes several types of software applications that support PU activities. These applications may be categorized into three types: *Decision*, *Financial*, and *Resource manager* classes. Examples of these kinds of software that can be considered as financial and resource managers applications are EMS and ERP. Specifically, it is worth to mentioning SAP and PeopleSoft which are software packages that support most of the financial activities of any enterprise. The *supports* association indicates all of the applications that support a determined PU, many of these applications may be shared by the PUs. Similarly, *supports technology* association shows the relationship between *Application* and *IT* classes, which means that a software application can be supported by many kinds of information technologies. An interesting feature presented in figure 12 is the relationship among *IT*, *Production unit*, and *Resource*, where the association class named *Configuration* is used to register the different kinds of PU configurations that use applications and resources.

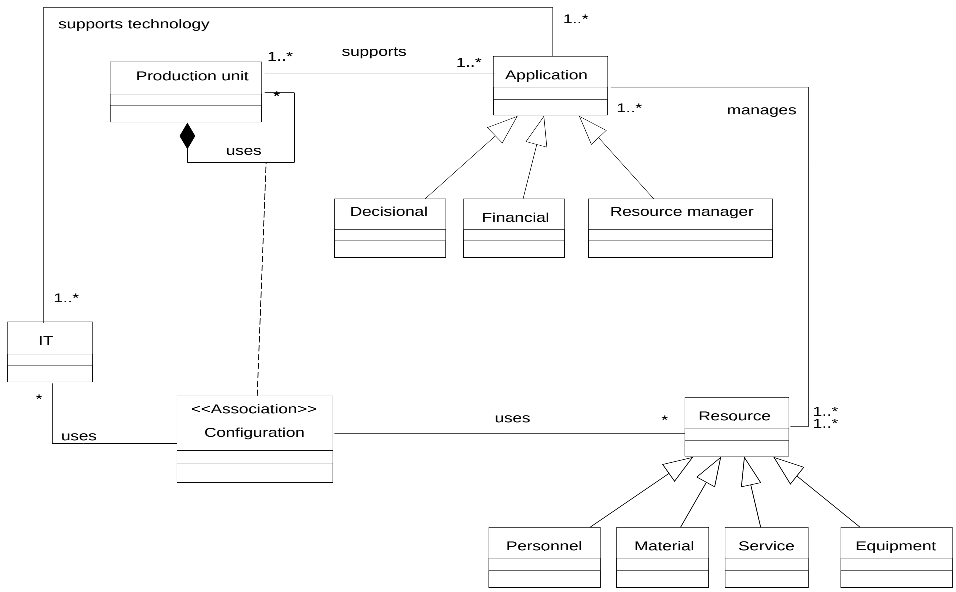

Fig. 12. Object Model for the integrated system

4.1 The Implementation Model

Figure 12 is taken as a base model to develop an implementation model of the integrated system. For that reason, the class *Application* is chosen as the model core class. If all of the applications used into an enterprise are registered, and CORBA interfaces for each one of them are built, then it is possible to integrate those applications. Additionally, some useful classes to model business rules and objects, (which permit the representation and register the evolution of objects and rules related to PUs applications) may be considered. One special application named the integrator agent is included. This application is a software agent responsible for synchronizing, maintaining, and controlling all of the integrated applications.

5 An Application Example

The following example illustrates the ability of the proposed approach for modeling a CPC that corresponds to a water treatment plant in a small Venezuelan city (City of Mérida).

Figure 13 depicts two important processes in a water system (i.e., commercial and production & treatment)in terms of a value chain. A brief description for each of the sub-processes involved in the production & treatment process is given below.

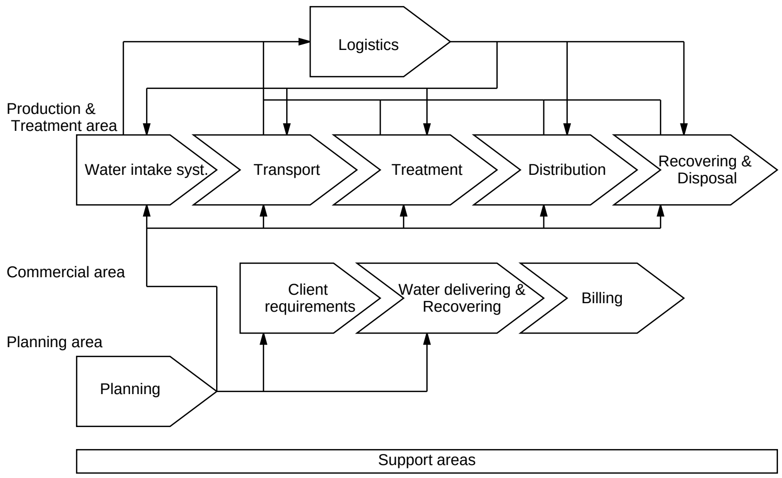

Fig. 13. Value chain for a water system

- **Water collection process**
  In general, water sources may be categorized as ground water and surface water. In this example, water is collected from surface water sources (i.e., rivers). The on-line functions control the quality and amount of water available. The long-term functions control the potential of seasonal production, the changes in the production potential, and the water quality from different sources.
- **Transport process**
  Water must be transported from the water-collection sites to the water-treatment plants and end-consumer sites. In this particular example, water is transported to the water-treatment plants by gravity. On-line decisions refer to the water-pressure at the treatment plants input and its volume; and the actions are the opening and closing of valves. On-line functions allow the detection of leaks and obstruction in the system. In the long-term, the capacity of transport facilities and new requirements of transport must be taken into account.
- **Treatment process**
  Water must be treated to improve its quality to an usable level. The treatment process is automatic and consists of the elimination of the water im-

purities by means of a filtration phase, as well as its disinfection by adding elements that eliminate and deactivate harmful viruses and toxic bacteria. On-line functions control the treatment, the determination of water quality, flow and pressure of treated-water measurements transmitted to the water-distribution system, and filters cleaning periods. Medium-term functions consist of maintenance activities.

- **Distribution process**
  After treatment, water is supplied by means of pumps or gravity to homes, commercial establishments, hospitals, fire department, water tanks, etc. It is necessary to maintain an adequate flow and pressure throughout the different points of the water-distribution system, detect leaks, and record water consumption in order to determine charges that allow the system operation and maintenance. Medium-term functions estimate new water-distribution networks requirements, and their posterior planning, financing, construction and operation.
- **Recovering and disposal process**
  Waste water must be recovered, treated and released to the environment. It is necessary to control and maintain water-treatment plants, maintain recovery systems, and estimate requirements (i.e. population and industrial growth) of new recovering and disposal systems.

Another process related to the afore mentioned sub-processes is called the logistics process which is needed to support the operational activities. The logistics process is composed of the following sub-processes: maintenance, inspection and material, and replacement parts acquisition and handling.

The commercial process is devoted to pay attention and accomplish the delivering of services to the population and get the retribution for these services.

The planning process performs the necessary calculation to estimate the growing of the needs and consider new sources, infrastructure and technologies in water systems.

5.1 Hierarchical automation architecture for the water system

As discussed throughout this paper, a CPC may be composed of several PUs. The decomposition of the described water system into its PUs is made according to geographical considerations and/or functions (see figure 14). In this example, the water accumulation system has been decomposed into three PUs based on geographical location of the water sources: Mucujún, Santa Rosa and Los Curos. Also, the water-transportation system has been decomposed into three PUs that transport the water from the sources to the water-treatment plants or to water tanks.

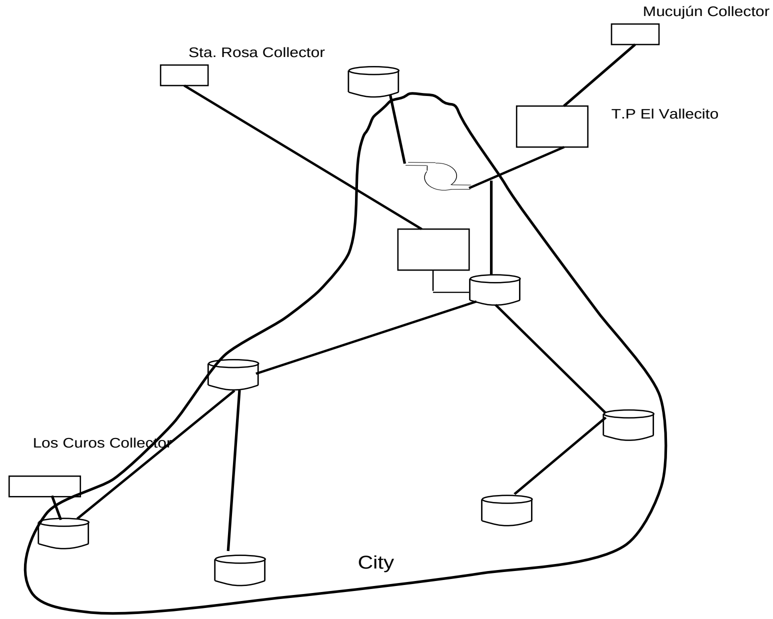

Fig. 14. City system

Figure 15 shows the integration of some elements of the integrated automation system that uses the control center as the principal data source for planning, programming and scheduling activities. The relation among the commercial system and the production system is achieved in terms of the set of water system objects that allows to describe common objects and mobilize those objects among the existent applications.

Main benefits obtained and others expected by applying the before presented approach can be sumarized as:

(1) Energy and chemicals consumption reduction.
(2) Improvement of information exvhange between MES and other applications.
(3) A better response to systems maintenance due to automatic failure detection and reportin activities.

6 Conclusions and further works

This work has presented an enterprise three axes integration model (3D-EBM), which allows the definition of the information flows among enterprise components and captures the relationships among support areas, production processes and decision systems. It may be used with the business value chain model in order to obtain an easy definition of business objects for a continuous production complex.

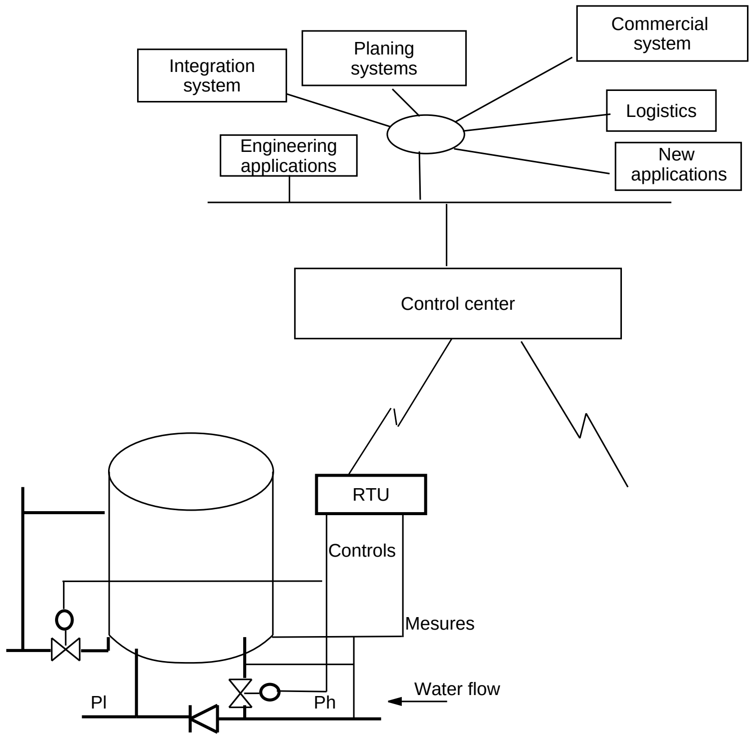

Fig. 15. Applications integrated and to be developed later

On the other hand, a schema based upon the feedback control approach, has been included into the model in order to implement decision making procedures, which can operate in an automatic or semi-automatic way by integrating phases, business objects and control algorithms. The model facilitates the description of links with software applications that allow to perform specific tasks for each one of the stages on a decision cycle. In order to facilitate the implementation description, the Production Units behaviour can also be described in terms of formal Objects Oriented techniques. The paper has also presented an introduction to the implementation phase taking into consideration elements of the whole system and using common technologies platforms such as SCADA, DBM, and ERP packages.

Research is underway in order to obtain a generalized description method for the business rules, which may be used to generate the specification of the Business Objects and Rules in a common framework, and to structure new applications to be developed or old ones to be integrated into the whole system. Also an effort is being given in order to derive a behaviour description, which is important as an element for the verification of the model behaviour and may be used to generate the states that must be inserted in the implementation model for the PU.

7 Acknowledgements

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Appendix A

Data flow description

- **Flow 1** corresponds to information going from support functions to specialized systems. This information may be used to obtain indicators about the financial state, cash flow availability, proposed budget, assets values, accounting, sales orders, etc.
- **Flow 2** indicates the information going from the systems that generates financial and resources indicators to the decision systems. Indicators are different for each decision level.
- **Flow 3**. Engineering information necessary for the decision-making systems is obtained from specialized models of PUs, relations and dependency among the PUs.
- **Flow 4**. Work orders coming from scheduling systems to the PUs.
- **Flow 5**. Information from decision systems to support systems, such as bill of materials, production levels, material reception, products delivering. This is an economical information over the compromises that must be honored by the accounting systems.
- **Flow 6** is the decision information flow: Mission, plans, work orders, commitments, adopted budget, etc. These decisions indicate how the PUs and the support areas must cooperate.
- **Flow 7**. Bi-directional flow corresponding to production process variables, PU state, failures, which allows to perform the coordination activities over the PUs.
- **Flow 8**. Support areas must facilitate the essential activities over the enterprise. Cash flow must guarantee the acquisition of the human resources, raw material, improvement and maintenance of assets, upon the scheduled activities.
- **Flow9**. To make the economical account of the production systems and report of activities, PUs must give information to the support systems.

Planes description

The model presents three principal planes, the engineering plane, the economical restriction plane, and the support information exchange plane.

The engineering plane

The engineering plane evaluates:

- Capabilities of each unit plant under different operation modes.
- Real performance of each unit and expected performance. Mass balance, Energy balance.
- Availability of the plant and equipment condition.
  - Evaluation by the process data.
  - Inspection activities.
  - Maintenance policies.
- Operational costs.
  - Cost accounting.
  - Materials.
  - Energy.
  - Waste disposal.
  - Human Resources.
  - Production.
- Products delivering.
- Materials management.
  - Inventory management.
- For the whole process, the same considerations are made.

Restrictions evaluation plane

On the other side, support systems help in the management of:

- Financial management activities.
- Cost allocation activities.
- Procurement activities,
- Marketing,
- Human Resources management.

Appendix B: UML Class Notation

UML is a standard adopted by OMG as a software modeling language [17]. In this paper, we used the class diagram notation for representing the entities of a production unit and their relationships. The meaning of the symbols used in the class diagrams is as follows:

- Classes of entities, things or concepts are represented by rectangles.
- A free association between two classes is represented by a line.
- A part-of or composition relationship between a composite class C and a component class is represented by a line with a filled diamond at the end connected to C.
- An aggregation relationship between a class C and its aggregate class is represented by a line with a hollow diamond at the end connected to C.
- A specialization or superclass/subclass relationship is represented by a line with a hollow arrow at the end pointing to the superclass.
- An association class is connected to an association between two existing classes.

Figure 16 shows the UML symbols used in this paper.

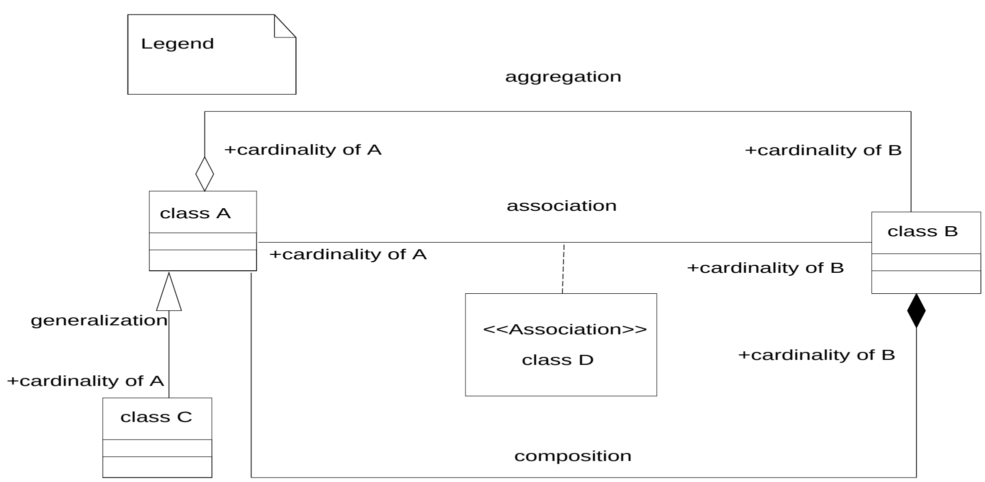

Fig. 16. UML symbols

Appendix C: Acronisms

CIM: Computer Integrated Manufacturing

CIP: Computer Integrated Processing

CPC: Continuous Production Complex

CORBA: Common Object Request Broker Architecture

DCM: Decision Making Cycle

DES: Discrete Event Dynamics Systems

DMP: Decision Making Procedures

ERP: Enterprise Resource Planning

MES: Manufacturing Execution System

PCx: Production Complex

PU: Production Unit

UML: Unified Modeling Language