

HYBRID APPROACH TO AIR CONDITIONING SYSTEMS MODELLING USING PETRI NET

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***Abstract.** The concept of intelligent building is being reconsidered to improve the rational use of resources, especially energy, and the need to ensure productivity and quality in the execution of activities. The building environment should materialize the concept of integrating building systems and effectively optimize resources and efficiency of human labor. In this context, conceptual approaches based on hybrid and discrete event system techniques derived from the Petri net, have been introduced as an effective alternative for modeling and analysis the integration of the building systems. Then, currently there are some methods for modeling and analyzing the control strategies of air conditioning management systems where the influence of discrete events and continuous dynamic is considered. However, these methods and approaches are limited to their ad hoc implementation solutions, such as air conditioning systems based on continuous volume of air. Thus, this work introduces an extension of these approaches to model and analyze the building automation solutions that include air conditioning systems with variable volume of air. The efficiency of this method in the design and validation of these solutions is illustrated through an example of application.*

***Keywords:** Petri net; intelligent building; hybrid system; modeling; air conditioning*

1. INTRODUCTION

In the current global context, the use of resources in an economic and sustainable way is a fundamental prerequisite to the project of new productive systems. In particular in the building facilities and in the infrastructure that is involved, these requirements are crucial to the financial viability of new industrial plants, commercial or residential. Among the main items that are being considered, there are the direct costs, which are related to the consumption of water, electricity, among others, and the indirect costs, which are related to the maintenance and the operation of systems that support the facilities. In the specific case of buildings, besides the economic issue, another important point in designing systems is to maximize the comfort and safety, which contribute significantly to increase the productivity and the satisfaction of the occupants (Villani and Miyagi, 2004).

In this context, the increasing technological advances in the automation area, evolving the technologies of communication, mechatronics and information processing permitted the consideration of the requirements as greater flexibility, safety and productivity in the design of new buildings (Sierra et al, 2005). Thus, the significance of intelligent building concept has been increasing, where a productive and economic environment is offered to the user by the optimization of four basic elements: structure, systems, services and maintenance, besides the inter-relationship among them.

An intelligent building, also called high-tech building, must attend, in the best way, the current and the future necessities of its users, providing resources for a more rational and economical management and integrate equipment and services in operational areas (Miyagi *et al.*, 2002). Among the sub-systems that compose an intelligent building, the air conditioning system has a special role, which significantly affects the economic aspect for being responsible, many times, for more than 60% of energy consumption in a building besides the costs of maintenance, as the aspects of productivity and satisfaction of users, once it is responsible for the thermal comfort of the users controlling parameters such as temperature, humidity and ambient air renewal (Creder, 2004).

The concept of intelligent building is closely linked to the effective integration of sub-systems that control the productive activities in a building. When there is no effective communication among them, the result is often contrary to what is desired, providing actions incompatible or unwanted, increasing operating and maintenance costs (Bolzani, 2004). The reliability in the functioning of the integrated systems in an intelligent building can be assured only through appropriate techniques for modeling and simulation that have been developed for the analysis of the behavior and interaction among the parties. The vanguard of the technological advances in this area is precisely in developing these techniques of modeling and simulation, especially for the evaluation of practical situations, even with the growing

complexity. Within the presented context, in (Villani and Miyagi, 2004) it is proposed a method for modeling and simulation of air conditioning systems in intelligent buildings. This method uses a hybrid approach, where discrete aspects and continuous process are considered, emphasizing strategies that involve interfaces with other systems of the building. This method starts with the use of interpreted Petri nets for the construction of models (Miyagi, 1996) and, from these models the active and passive parts of the system are characterized, obtaining a detailed structural and functional model of the air conditioning system in a Petri net, which includes continuous variables described by differential equations.

This work explores this method, and expands it to other management structures of air conditioning system. The aspect of thermal production, and the air conditioning distribution are now considered. Among the contributions of this work, there are the extension of the method for systems with variable volume of air (VAV), the performance of equipment, and the inclusion of protection for critical equipment such as compressors. An example is presented to illustrate the effectiveness of the developed method. For this example, the management strategies to be adopted were considered, that its suitability was evaluated relating to the configuration of the building. Afterwards, the dynamic models were developed. It includes the activities of management of the air conditioning system, local control and behavior of the environment, and the integration of them. Once constructed the models, the simulation is used for validation and analysis of strategies. Thus the developed method considers a process of continuous improvement to obtain the most appropriate solutions for management of building operations.

2. MODELLING OF SYSTEMS

2.1 Systems Classification

A possible classification for productivity systems is based on the characterization of its state variable in relation to the time (Cardoso and Vallete, 1997). In this sense, discrete events systems (DESS) are characterized by occurrence of instantaneous transitions among discrete states. The state variables vary abruptly in certain moments. These systems are generally based on rules and procedures that are defined by man. For this type of system, the goal is to control the execution of transactions, characterized by the occurrence of instantaneous events and maintenance of discrete states, through a pre-defined procedure.

However, there are continuous variables systems (CVSS), which the main characteristic is that the behaviors of the state variables are defined by phenomena of the nature, generally governed by physical laws that are continuous in the time. For its modeling, the differential equations are effective proved tools. In these systems, the basic objective of control is, usually, equal the value of a variable control to a reference value.

From these concepts, the concept of hybrid systems is derived, involving the continuous variables, and also interferences, which are defined by discrete events. There are here characteristics of DESS and also of CVSS. A practical example is the air conditioning system in buildings where there are discrete states, which are characterized by equipment forecast commands, and continuous variables in time, as the signs of the temperature sensors, besides the interaction with entities from other systems, such as the fire combat system, the users access system, the lighting system and so on, as shown in Fig. 1 (Villani *et al.*, 2005).

For modeling of hybrid systems, there are two strands of approach. One is based on extensions of continuous models, with the inclusion of discrete variables. The other is based on modeling techniques that are used in DESS, as Petri net, with the inclusion of elements, representing a continuous change in time. As the focus of this work is in management of the system, which presents discrete nature, the second approach was considered. In (Villani *et al.*, 2005), it is presented an analysis of the proposals in the literature for extensions of Petri Net for modeling of hybrid systems. The Differential Predicate Transition Petri net is identified as the most suitable for an air conditioning system modeling, because it allows the representation of discrete variables and also the continuous dynamic, which is associated with the air and the heat flow through differential equations systems. This formalism is also used in this work exploring the flexibility and the extension of the modeling method proposed in (Villani and Miyagi, 2004).

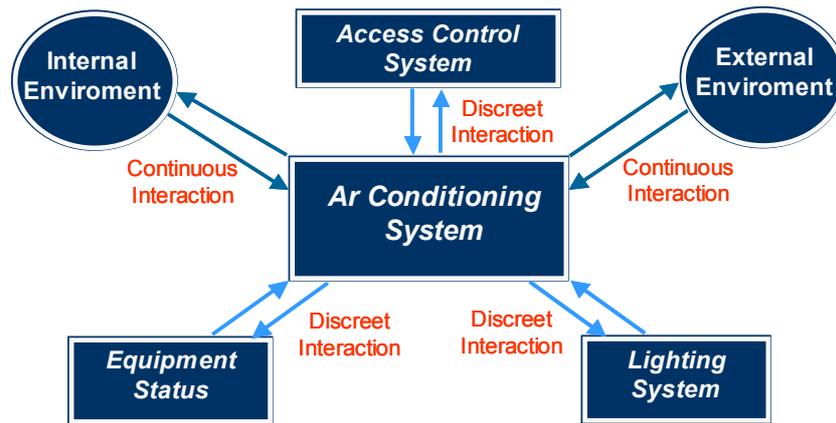


Figure 1. Interactions of the air conditioning system in an intelligent building.

2.2 Differential Predicate Transition Petri net (DPT net)

The Differential Predicate Transition Petri net (Villani *et al.*, 2005) provides a framework to combine Petri net and differential equations systems. In CVSs, a particular set of differential equations defines the evolution of continuous variables. In the case of hybrid systems, this set of differential equations is defined in accordance with the occurrence of discrete events. Thus, in Differential Predicate Transition Petri net, differential equations systems are associated with “places” (structural element of Petri net) and continuous variables are associated with the “token” (another structural element of Petri net). Thus, it is possible to represent several discrete configurations, modeled in Petri net, and the representation of the continuing evolution of the system, modeled by differential equations associated with number of tokens in the places, for each of the configurations. Differential Predicate Transition Petri net that is “marked” (a Petri net with a distribution of tokens in the places) can be defined by $DPT = \langle R, A, M_0 \rangle$, where:

- R is a Petri net, which is defined by $\langle P, T, Pre, Pos \rangle$
 - P is a set of places;
 - T is a set of transitions;
 - Pre is a mapping from places to transitions;
 - Pos is a mapping from transitions to places;
- A is the inscription of DPT, $A = \langle X, AP, AC, AA, AF \rangle$, where:
 - X is a set of variables, whose value is a real number;
 - AP associates for each place a vector of variables X_{pi} belonging to X ;
 - AC associates a function of habilitation e_i to each transition;
 - AA associates a function of junction j_i to each transition;
 - AF associates a system of differential equations F_i , whose variables are X_{pi} .
- M_0 is the R initial marking.

The “transition firing” rules are derived from the conventional Petri net but additional conditions are considered to treat the continuous variables. An example of transition firing in a Differential Predicate Transition Petri net (DPT net) is shown in Fig. 2. The dynamic evolution of the net is defined not only by the firing of transitions, but also by the continuing evolution of variables associated with the tokens in the places. This behavior is determined by the set of equations that is associated with the place where the mark is.

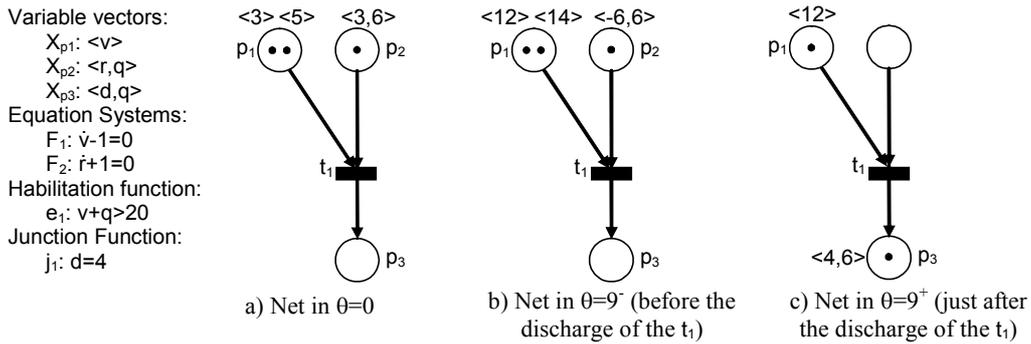


Figure 2. Transition firing example in Differential Predicate Transition Petri net (where θ is the time variable).

Once the transition is enabled, and the habilitation function has its conditions attended; it fires immediately, and the junction function determines the new values of the variables associated to the output places.

3. PROPOSED METHOD

3.1. Original Procedure

The original procedure (Villani and Miyagi, 2004) involves the definition of an interface between two models to allow greater flexibility in modeling both the continuous and discrete part. It is based on a hierarchical approach that gradually breakdown the models that describe the system. The procedure is organized in three main stages:

a) Definition of strategies: The focus here is the definition of the sequence of events and actions of each operation and control strategy, the components of the air conditioning system on which the strategy works, and in which situations it must be activated. After the definition of each strategy, its influence on the internal and external environment must be specified, that is, it is necessary to establish the expected air flows, water flows, temperatures, pressures, air humidity, etc., since its inclusion in the management system are directly associated with the environment properties. It is also necessary to specify the interfaces of each strategy with the management system of the air conditioning system, and with other systems of the building, since their actions will affect or influence them.

b) Construction of models: In this stage, the modeling of the air conditioning process, the local control of each equipment, the management system, and the internal environments, are developed. These models must be developed considering their posterior integration, as shown in Fig. 3.

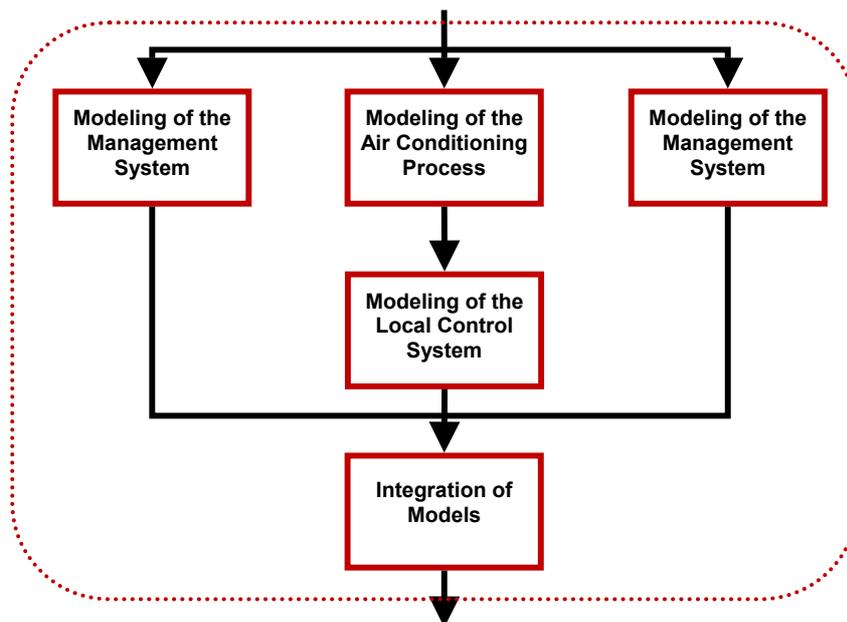


Figure 3. Details of the construction phase of models.

To obtain the Petri net model of the system, it is used the technique of successive refinements based on PFS (Production Flow Schema) (Miyagi, 1996). A top-down approach is used, based on the concept of macro-events, that is, activities that may include several states and other events that are organized hierarchically. The system is then characterized by the activities that are performed on a flow of items (objects, materials, information, etc.). Thus, each production process is described by a set of active elements (activities), passive elements (distributors) and oriented arcs that indicated the relationship between the previous elements. This model in PFS is then gradually refined, generating a model in conventional Place/Transition Petri net with enabling and inhibiting arcs (Miyagi, 1996) (Cardoso and Vallete, 1997). These arcs are used to model the exchange of signals between management system and the drives of the equipment/devices. These signals can be represented by boolean expressions.

The model of the management system is composed by different strategies of control, previously defined, and the number of operations performed on the air conditioning system that are concretely executed by local control systems, responsible for interface with the actuators, sensors and devices for communication with the local operator or user. The modeling of local control system must consider the states of all items that compose the system. For the modeling of the air conditioning process both the flow of air and water are modeled as variables as well as temperature and pressure. Therefore these variables are associated to places where a set of differential equations determines the expected behavior in accordance with its physical properties. The internal environments are also modeled by a set of differential equations that represent the variation of the properties of air in these spaces, depending on the heat received, which may also be influenced by discrete events, like the number of people in the rooms and number of activated lamps and equipment. The association of variables and its dynamic behaviors with the places and arcs of the Petri net models must follow the definition of DPT net.

The integrated behavior of the models of management system, air conditioning process and local control systems is determined by the signals in the enabling and inhibitor arcs. The integration of the air conditioning system with the environment is achieved through the specification of the mutual influences between continuous variables characteristics of the environment with the elements of the air conditioning system.

c) Analysis of models: The analysis of models initially considers the validation of the Petri net structure, i.e., the structural properties must be respected in order to assure that the models have a description that is a DPT net, and its structural and behavior properties can be explored to evaluate the modeled system. Thus, the characteristics of the model developed for the management strategies of the air conditioning system are identified. This procedure is used to verify that the logical structure of the model is in accordance with the specifications of the air conditioning system. The next step involves the study of dynamic properties of the model. This is based on the rules of evolution of the DPT net, where it is analyzed the dynamic of the model developed, concerning management strategies of the air conditioning system. The model in the DPT net allows the mapping of all states reached by the system, however, in practical cases, it is generally not feasible due to the relatively large number of possibilities. Thus, the procedure adopted is the study of scenarios through the use of simulation. This step involves the use of simulation techniques for discrete parts that are modeled by discrete variables and numerical simulation for the parts that are modeled by differential equations. The analysis of the overall hybrid model is performed linking the two simulations mentioned. For the simulation of the discrete part of the system, it is considered the model in DPT net, with the elimination of elements concerning differential algebraic equations. The resulting model consists of only elements of a Place/Transition Petri net with enabling and inhibiting arcs. This model includes the management system and the discrete parts of the air conditioning process, and the local control systems. This simulation can be performed using computational tools available, such as Visual Object Net (Drath, 2003), and HPSim (Anschuetz, 2002). With this simulation it is possible to analyze and validate the logical operation of the models. For the simulation of the continuous part, tools such as MatLab can be used to numerically compute the differential equations associated with the marking in the DPT net that models the air conditioning process, local control systems, and the environment. This is used to check if there is a consistent behavior of the continuous variables considered in the context of specific situations. A hybrid simulation of the system involves the synchronized evolution of the simulation of discrete and continuous parts, which are specified by the marking and occurrence of events in the DPT net.

3.2. Improvements in the Procedure

In this paper the method proposed in (Villani and Miyagi, 2004) is expanded to include new configurations for management and control of air conditioning system, including the control system with VAV (variable air volume) and variable speed pumps and fans. The main changes introduced in the method are summarized in the following items: (i) modeling the variation of cooling capacity of the chillers; (ii) modeling systems of VAV, which involves the regulation of air pressure over the air conditioning system; (iii) modeling the interface between continuous and discrete dynamics for the flow of water and air. These items are detailed below.

a) Variation of cooling capacity of the chillers: the implementation of new technologies allows the operation of equipment with a variation of performance. The chillers are devices where their compressors can operate in various speeds, in other words, with different performances. The same operational function can be considered for centrifugal pumps that use frequency inverters for variable speed motor and the consequent change in the flow of liquid. In this

sense, the model for local control of this equipment must be reviewed to ensure that the control explores this type of versatility. The control strategy must include the regulation or adjustment of performance of the devices. Figure 4 illustrates an example of a DPT net for the local control system of a chiller with different capacities to work (0%, 25%, 50%, 75%, and 100%), which may be characterized as discrete modes of operation.

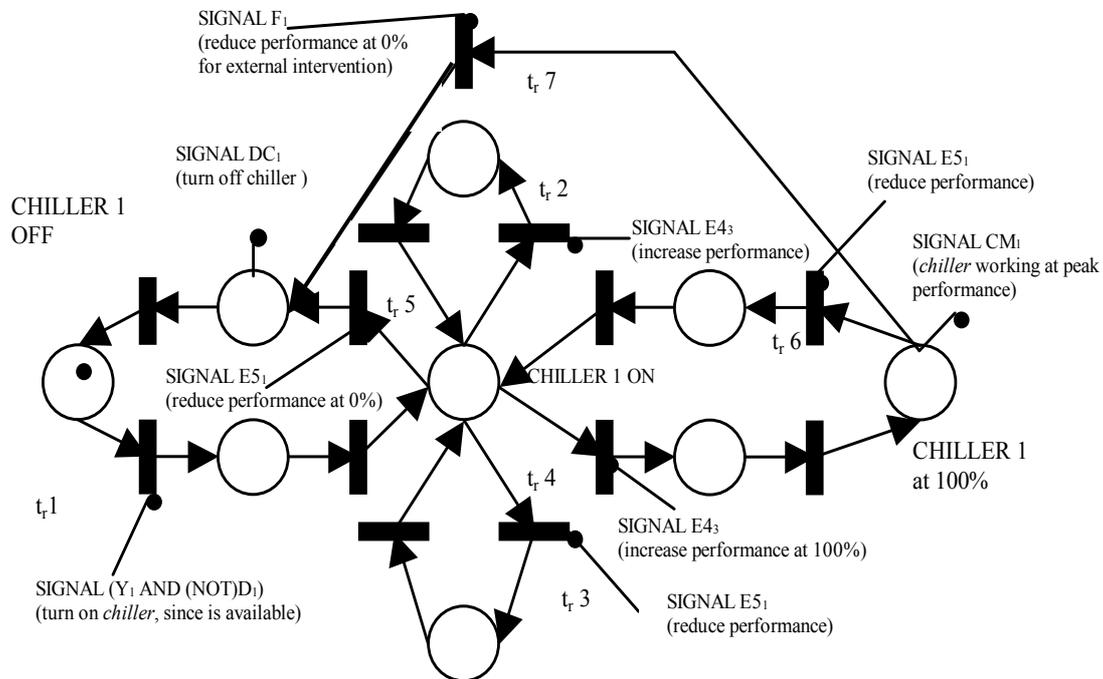


Figure 4. Model of the local control system for operation of chiller 1.

b) Air conditioning systems with VAV: another point for review and improvement of the method concerns with variable pressure in the systems. In the original method, this property was not considered, since the variations of pressure, both from the air as the water, did not interfere in the control system. With the new techniques that consider the equipment performance variation, the pressure becomes a relevant variable in the control system.

c) Interface between continuous and discrete dynamics of water flow and air flow: another aspect to be considered for improving the method is that the models that represent the continuous variation of fluids properties and the environment are disconnected from the models of the functional states of the control system. The relationship between the equations of the air flow and water flow with the air conditioning process is done by the sharing of variables among the differential equations. Therefore, as previously mentioned, in the simulation, the discrete and continuous simulators must evolve in synchronized mode. The idea here is to join the discrete model of the air flow and water flow relating these dynamics in the differential equations. The resulting model represents the discretization of the solution of differential equations, which also occurs in the case of computer simulation of continuous models. Thus, the DPTnet also indicates the sequence of solving differential equations, which corresponds to the path traveled by the fluid (water or air). To ensure proper update of variables values related to the continuous dynamics, it is introduced a complementary place for each place (marked places in the DPT net of Fig. 5). Thus, the value of the variable is updated with the token presence or absence in the places in accordance with the modeled flow. As an example, Fig. 5 presents a model for flow division of a system with two chillers that operate in parallel. This model includes the process of cooling water in a mixing equipment, and the cold-water flow that goes to the secondary pumps. If one of the equipment is out of operation, there is an alternative to continue to maintain the air conditioning.

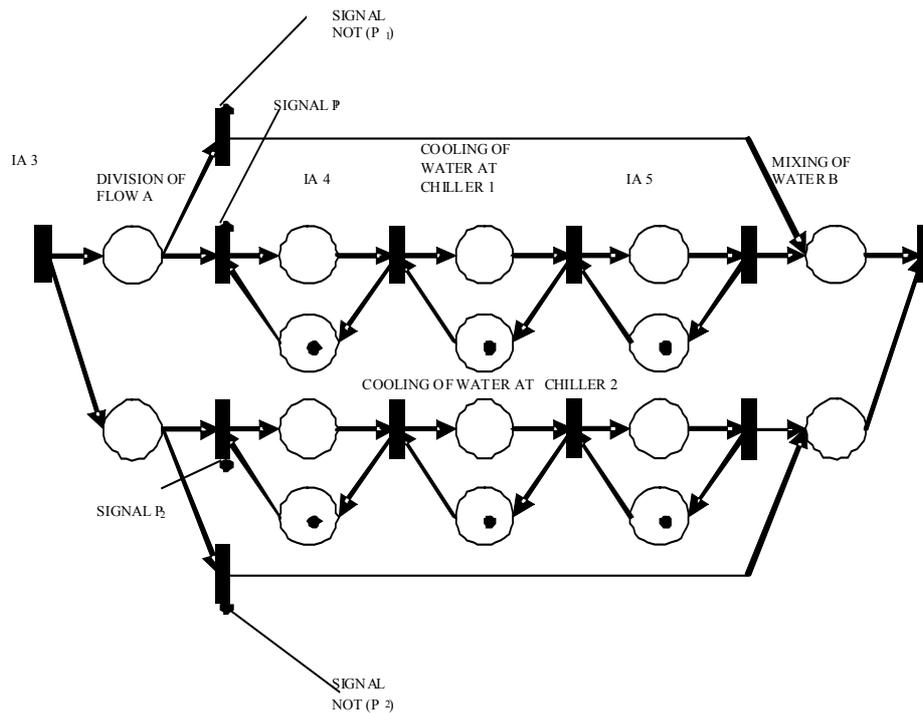


Figure 5. Model the process of cold-water flow in the chiller.

4. EXAMPLE

In this work, the SENAI/CIMATEC building in Salvador, BA, was used as case study. This building can not be considered an intelligent building, since several of its activities are not automated, such as lighting systems, fire fighting or access control, and even those that are automated are not properly integrated. However, the configuration of its air conditioning system allows the development and analysis of the proposed method for modeling and simulation. A management hybrid system can be considered in the context of the needs and expectations of this work. Among its main characteristics, it is detached the air conditioning process by indirect expansion, using cold-water, primary and secondary pumps for their distribution to the fan-coils, with regulation of the cold-water flow and air temperature, through systems with VAC (constant volume of air), VAV, and VAV with alternative cooling system (split system).

Due the space restrictions, in this paper only an example of the studies conducted in the case study is presented to illustrate the validation and efficiency of the improved method.

After the modeling task, where samples of some specific cases are illustrated in Fig. 4 and 5, it is possible to start the analysis stage. For detailed information about all generated models, see (Almeida, 2008).

The analysis of the model is developed considering specific scenarios where certain properties are studied to validate the operation strategies of the air conditioning system. Thus, the simulation of the discrete part involving flow of fluids, management strategies, local control system, and their interactions, is performed using the software Visual Object Net (Drath, 2003). This tool was considered here due its flexibility and ease of use of Place/Transition Petri nets with enabling and inhibitor arcs. Furthermore, it provides the use of timer transitions and a special type of places and transitions where the continuous behavior of the variables can be invoked, that is, the part related to continuous variables involves additional functions that can be implemented in MatLab or other similar tools.

Several flows in the air conditioning system were identified on the modeling procedure. Simulations were performed for each flow, considering assumptions representing possible situations for real system, like in the following example:

Example (1) - Simulation of the cold-water process (Fig. 6): For the simulations of the production process of cold-water were used the following models:

- Local control system of chillers 1 and 2;
- Local control system of primary pumps 1 and 2;
- Local control system of secondary pumps 1, 2 and 3;
- Performance control system of chillers 1 and 2;

- Operation strategy for [Increasing the production of cold-water]¹;
- Operation strategy for [Reduction in the production of cold-water];
- Flow of cold-water.

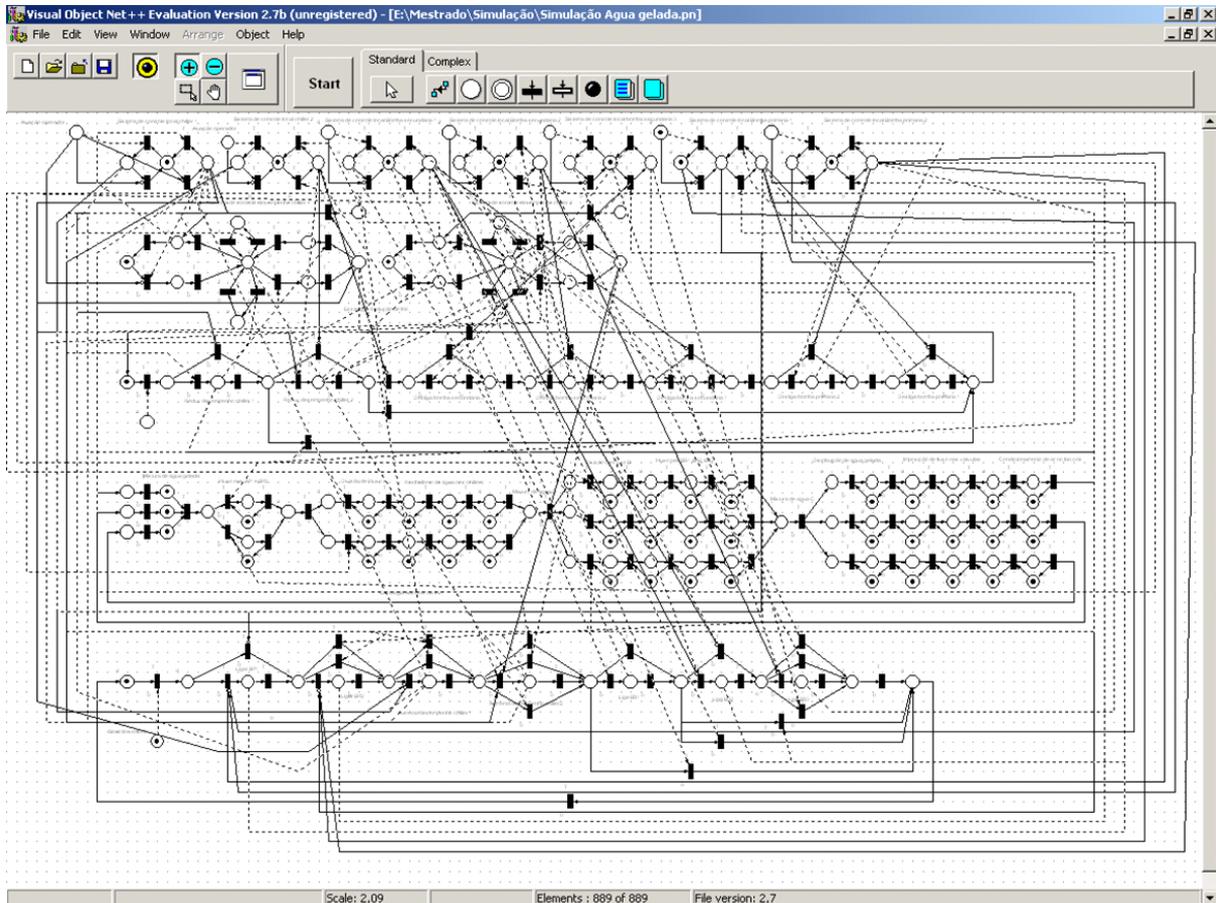


Figure 6 – Cold-water flow model in Visual Object Net simulator

a1) Simulation case 1: all the equipments were available, according to the following order of priority:

- Primary pumps - BP1 and BP2;
- Secondary pumps - BS1, BS2 and BS3;
- Chillers - chiller 1 and chiller 2.

Initially the system was considered at rest, without any activity. Then the initial strategy for [Increasing the production of cold-water] is activated. After starting the strategy, it is imposed a sensor signal indicating that the temperature is above the set-point. The simulation consequently shows the following sequence of events:

- Activation of the primary pump 1;
- Starting the flow of cold-water;
- Activation of the secondary pump 1;
- Activation of the performance control of the chiller.

Keeping the enabling signal of the strategy [Increasing the production of cold-water], there is a gradual increase in the performance of the chiller 1, until it reaches 100%. If the strategy is maintained, the chiller 2 is activated; presenting a gradual increase in its performance until it also reaches 100%. In accordance with the functional specification, if necessary the model of the discrete part triggers the activation of secondary pump. To increase the flow, secondary pumps can be triggered automatically.

¹ An “activity” in PFS graph is identified by an inscription between “[” and “]” describing the activity considered.

When the enabling signal of the strategy [Increasing the production of cold] is turned off, the strategy [Reduction in the production of cold] can be activated, that is, it must be effectively activated when the water temperature is below of a specified value and it is necessary the return to the specified set point. Then, the following sequence of events occurs:

- Gradual reduction in the performance of the chiller 2 (100% to 0%);
- Shutdown of chiller 2 and disruption of the related flow;
- Gradual reduction of the performance of the chiller 1 (100% to 0%);
- Shutdown of chiller 1 and interruption of related flow;
- Shutdown the secondary pump;
- Shutdown the primary pump;
- Interruption of the cold-water flow.

The experiments confirm that both sequences of events in the model faithfully reproduce the expected sequence of events in the real system.

The procedure illustrated on item 3.2 conducts the system analysis, considering other operational cases and scenarios. Then, the simulation technique is used to confirm the expected sequence of events, overall performance, abnormal situations, and also to collect data for reliability analysis.

5. FINAL REMARKS

Among the trends in rational use of resources, especially energy, and the need for productivity and quality in the implementation of productive activities, there is the plant infrastructure that exploits the concept of intelligent building. This environment embodies the concept of integrated systems powering the optimization of natural resources and efficiency of human labor. This study addressed the integration of the air conditioning system, whose importance is evidenced by its effect in the comfort of the users, equipment performance, and to be a high energy consumption sub-system in any intelligent building.

The conceptual approach is based on discrete event systems and techniques derived from the Petri net that are adopted as an efficient alternative to modeling and analysis of systems integration solutions. This work presents the improvements in the procedure proposed by (Villani and Miyagi, 2004), expanding it to other management structures of the air conditioning system. New considerations are introduced in both the modeling aspect of the production as well as the distribution of conditioned air and water in the air conditioning system. The contributions of this work includes the extension of the method for systems with variable air volume (VAV), the performance control of the equipment, and the protection for critical equipment such as compressors. Moreover, it presents a different approach to modeling the air and water flows considering a Petri net representation of the continuous dynamics.

To test and validate the improvements in the existing method, case studies were developed. In these studies, the management strategies are evaluated to check if they are suitable for different configurations of the building.

The studies realized confirm that the resulting method is effective for developing strategies for management of air conditioning systems. The method can be used to explore different possibilities before physical implementation, enabling the optimal use of resources. It allows the verification of the adequacy of the operational strategies for the air conditioning system.

The conducted experiments also to confirm the versatility of DPT net to describe and detail the integration of systems of intelligent building. In this context, the systematization of the modeling procedures actually contributes to the rationalization and standardization of models generated, that are fundamental for the design and analysis of systems, and also for its maintenance and future enhancements.

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6. RESPONSIBILITY NOTICE

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