MODELING OF FIRE PROTECTION SYSTEMS IN INTELLIGENT BUILDINGS

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Abstract. *A mechatronic approach is essential in intelligent buildings (IB) to effectively integrate a number of services and systems such as elevators, power systems, heating ventilation and air conditioning, lighting and fire protection system (FPS). From the point of view of property damage and personal security, the FPS is one of the most important systems in an IB. The FPS is composed of many devices and control strategies. Furthermore, it must act in acordance with specific laws. As a consequence the design of FPSs is a complex task and it is very important to provide an adequate model that supports the verification of the FPS dynamics and its integration with others building systems, facilitating its test and validation. In this context, this work proposes a procedure to model in a systematic and rational way a FPS in the IB context. Considering the nature of the structure and processes of FPS the approach is based on the discrete event dynamic system theory and the application of the Petri net. The approach models the FPS control system and the controlled plant including its integration with other building systems. Particularly, it explores Petri net extensions such as Production Flow Schema and Mark Flow Graph techniques. Through an example it is illustrated the main aspects of the proposed procedure.*

Keywords: *Intelligent Building, Petri net, Fire Protection System, Modeling, Discrete Event Dynamic System.*

1. Introduction

In intelligent buildings (IB) a mechatronic approach is applied to effectively integrate services and systems such as the elevator system, power systems, heating, ventilation and air conditioning system, lighting system and fire protection system (FPS). The purpose of this integration is to create an environment that results in low costs and better efficiency, productivity, security and safeness when compared with conventional building (Flax 1991; Kroner 1997; Miyagi et al., 2002; Wang et al., 2005).

From the point of view of property damages and personal injuries, the FPS is one of the most important systems in an IB. According to NFPA (1997), the main goals of FPS in a building are to:

- Guarantee human safety;
- Ensure material protection; and
- Maintain the continuity of the activities performed by the building occupants.

As a result, the FPS operation must be the object of a careful analysis, considering particularly its influence in people and building safety. Furthermore, the FPS is responsible for different procedures and must act in accordance with specific laws. An adequate modeling is therefore of significant importance for the verification of the system dynamics and its integration with other building systems.

Some works approach the problem of modeling the FPS behavior. However, they consider specific installations (special rooms, industrial environment, etc.) and they do not model or analyze the integration of the FPS with other building systems (Olenick; Carpenter, 2003). In fact, there is a lack of specific work about this subject. Therefore, this work introduces a modeling procedure that focus on the integration of FPS with other building systems. For this purpose, this work considers the FPS as a Discrete Event Dynamic System (DEDS) (Peterson, 1981).

The proposed approach starts, in a first stage, with the conceptual description of the system processes. It then applies techniques derived from Petri net, such as Production Flow Schema (PFS) (Miyagi, 1996) and Mark Flow Graph (MFG) (Hasegawa et al., 1987) to develop dynamic models of the FPS integrated with other building systems. The models generated are then validated according to the FPS requirements and verified according to Petri net properties (Murata, 1989).

This paper is organized as follows: in Section 2, the intelligent building concept is presented along with its main functions and features, emphasizing the importance of FPS integration with other building systems. In Section 3, the devices that compose the FPS are discussed and their dynamic behavior is characterized by the occurrence of discrete events. In Section 4, a technique derived from Petri net is presented. In Section 5, a methodology for modeling FPS is introduced. Section 6 presents a case study that illustrates the proposed methodology. Finally, the last section presents the main conclusions.

2. Intelligent Buildings (IB) and Fire Protection System (FPS)

In a conventional building, the systems such as elevators, water distribution, power systems, heating, ventilation and air conditioning, illumination and FPS works independently. Consequently, the building is not able to operate in situations that involve the conflict of resource demand, such as when the sum of electric energy demanded by the building system exceeds the available amount of energy. However, with the adoption of a mechatronic approach, the different systems are integrated exchanging information. The building is then able to react to demand variations in real time and with the best effective cost (Flax, 1991; Wang et al., 2005; Miyagi et al., 2002).

The main functions in IB are (Kroner, 1997):

- Security monitoring and activation of fire alarm system. Areas with human lives must have priority in case of emergency.
- Detection of human presence and/or occupation features in any building rooms. This information is used to operate the illumination, heating, ventilation and air conditioning control, based on preprogrammed procedures.
- Auto-diagnostic of the building components, such as machines and sensors.
- To optimize activation of elevators, escalators and other support systems that are used for moving people and other materials.
- Perception of the light intensity, angle and solar radiation, temperature and humidity, in order to adjust the building environment and achieve the desired level of performance.
- Acknowledgement of digital tracks or other way of biometric identification to control the access to the building;
- Odor and pollutants detection for ventilation control;
- Distribution of electric energy among equipments according to the demand or specified priority, and automatic activation of batteries and auxiliary generators.
- Ice banks and heat banks activation scheduled when the energy consumption rates are lowers.

The FPS integration with other building systems can result in operational and economics benefits. Examples include the smoke control, sharing sensors data, data acquisition in an emergency situation, availability of infrastructure, and new technologies for improving performance and safety (Bushby, 2001).

New sensors have also been developed to recognize several air contaminants agents that can indicate fire alarms or people threat. In an integrated system, these sensors can be used by the heating, ventilation and air conditioning system to control the airflow without having adverse impact on people safety (Tubbs, 2001).

The building access control system monitors the people inside the building and this information is essential to the FPS in case of emergencies. The firefighters may have the previous knowledge and look for occupants that need to be evacuated, reducing the risk to enter in unnecessary dangerous areas.

The FPS can use the sensor data of the integrated building system to calculate the heat propagation speed in case of fire and, using this data, can indicate problems in a monitoring panel to predict the fire growing and propagation. The firefighters can use these predictions to plan their strategies. This information can also be transmitted by the building communication system to the firefighter station or firefighter vehicle in order to make plans before they arrive in locus. The results are faster response time, which can save lives and reduce the material lost.

3. Fire Protection System (FPS) and Discrete Event Dynamic System (DEDS)

The FPS is composed of a set of devices destined to alert, as early as possible, the existence of initial fire, and fight it (NFPA, 1997). This system has the following components:

- Input devices: divided in (a) direct sensors, (b) indirect sensors, and (c) manual commands. Direct sensors are devices used to detect variations in building parameters that are influenced by the physical and chemical phenomenon related to an initial fire. The goal is to save time by anticipating the fire propagation. Indirect sensors are devices used to transmit information indirectly related with an occurrence of initial fire, such as thermostats in machines and equipment, pressure detectors, etc. Manual commands are devices used to transmit the information of an initial fire or emergency situation that are activated by the humans, such in manual procedures of breaking a glass and pressing a button.
- Alarm control panel: it processes the signals coming from direct sensors, indirect sensors and manual commands. It converts these signals in appropriated indications (monitoring signals) and activates the fight system components, i.e., output devices.
- Output devices: are composed (a) monitoring devices, such as, warning luminous lights, addressable audiovisuals alarms, and (b) actuation devices, such as actuation/deactivation contactors of fire resisting doors, HVAC dampers, solenoid valves and sprinkles.

- Interconnection nets: is the set of electric and communication circuits that interconnects the alarm control panel with the input devices, output devices, energy source and other building systems.

Once the alarm control panel receives a fire alarm coming from the input devices, it must process and perform a pre-established program, activating the output devices and sending information to other building systems. Fig. 1 shows a general structure of a FPS.

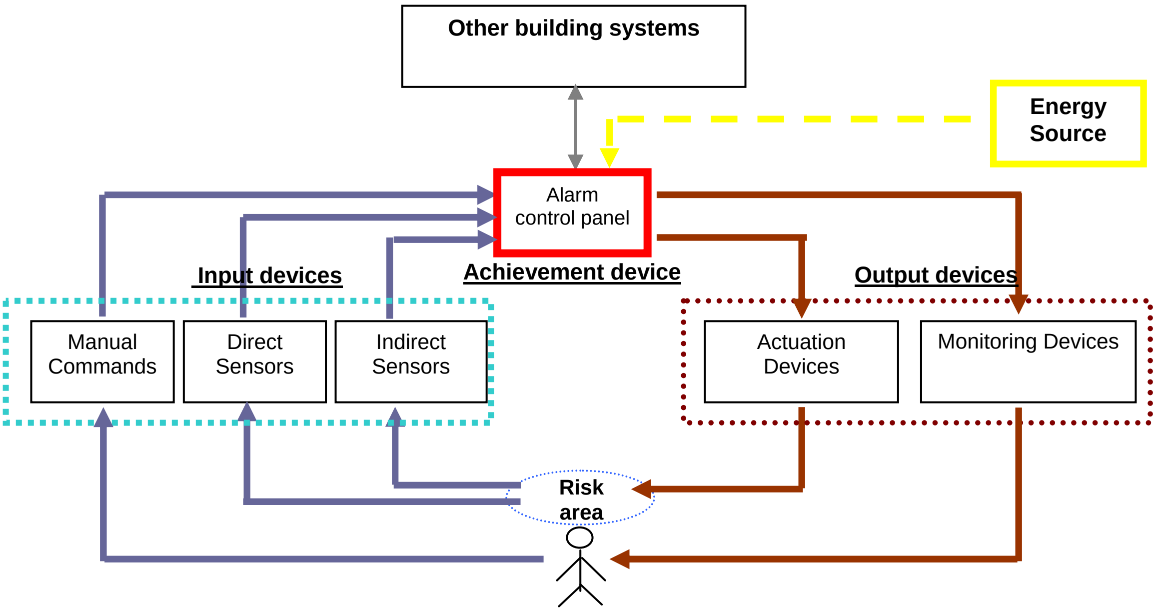

Figure 1. FPS general structure

The behavior of the FPS can be defined by a set of discrete states that are changed due to the occurrence of instantaneous discrete events. Examples of events are: activation and deactivation by detectors, activation and deactivation of warning signs, opening and closing dampers, activation and deactivation by manual commands, etc. This type of system can be classified as a Discrete Event Dynamic System (DEDS) (Reizig 1985; Murata 1989; Peterson 1981). There are several techniques for modeling, analyzing, controlling, and designing DEDS, such as Petri net, Markov chain, Queue Theory, Mini-max Algebra and State machines (Ramadge; Wonham, 1989). Among these techniques, Petri net has proved to be effective because of it graphic and formal description, among other reasons. Another important feature of Petri net is that the generated models can be automatically converted to programs that may be implemented in industrial controllers.

4. Petri net and its extensions for FPS

Petri net is a graphic and mathematical tool for modeling, analyzing, and designing DEDS. Among its main advantages have easy graphic interpretation, identifying states and actions in a clear way, and the possibility of representing the system dynamic and structure in many levels of detail (Murata 1989; Peterson 1981). Petri net can also model synchronism, asynchronism, concurrence, causality, conflict, and resource sharing.

Fig.2 shows some of the main characteristics of DEDS. In the synchronous process (see Fig.2a.), the event “detected fire” only starts when the events “detected high temperature” and “detected smoke” are finished. In the parallel process (see Fig.2b.), after the event alarm is activated, both procedures “turn on insufflators” and “turn on pump” are executed simultaneously. In the concurrent process (see Fig.2c.), after the alarm is activated, the system executes either a manual extinction or an automatic extinction. Finally, in the sequence (see Fig.2d.), the “turn on sprinkler” process is initiated only when the “turn on pump” process is finished.

Among the Petri net approaches for DEDS, the PFS/MFG methodology (Miyagi, 1996) is adopted. In the PFS/MFG methodology, an interpreted Petri net-based model of the system is built by using a top-down approach. Firstly, a conceptual model is obtained using the PFS (Production Flow Schema) technique (Miyagi; Arata, 1997). Then, the PFS model is refined into a functional model using MFG (Mark Flow Graph) (Hasegawa et al., 1987;) or some other specific type of Petri net (Hasegawa et al., 1999).

The aim of PFS is to identify the activities performed on a flow of discrete items (information or material) at a high level of abstraction. The PFS model has no dynamic. The components of PFS are activities, which represent modifications on the flow of items, inter-activities, which do not modify the items, and arcs (see Fig. 3).

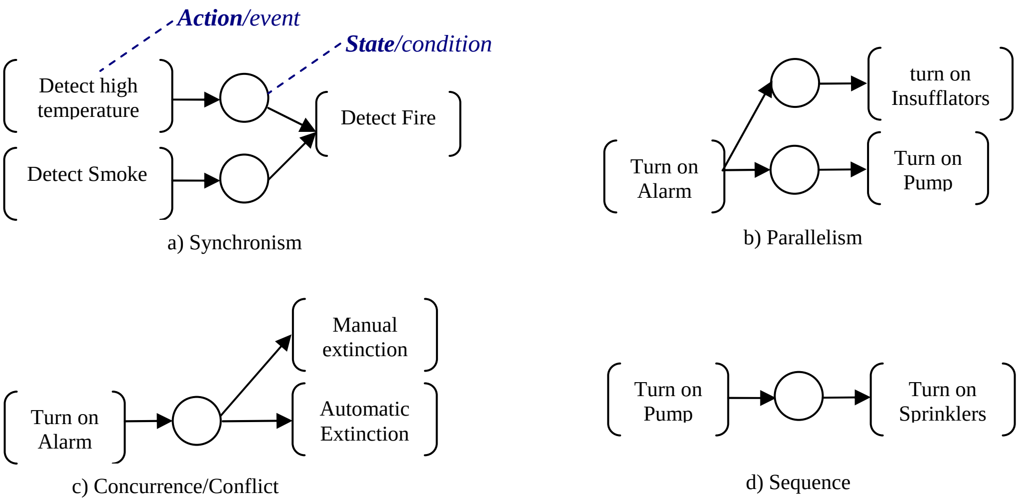

Figure 2. Characteristics of DEDS.

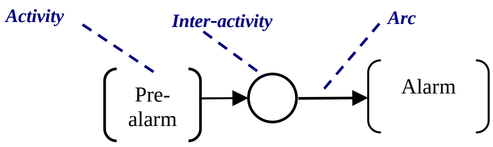

Figure 3. PFS components.

On the other hand, MFG explicitly shows the behavior of the activity and the interaction with external components. The MFG models the system dynamics by modifying the number and distribution of marks in the graph. The MFG consists of the following six elements: ***box***, ***transition***, ***directed arc***, ***mark***, ***gate arc***, and ***output signal arc***.

(1) A ***box*** represents a condition for an action (an event).
(2) A ***transition*** represents an event of the system.
(3) A ***directed arc*** connects a ***box*** and a ***transition***, and its direction shows the input/output relation between them.
(4) A ***mark*** is placed in a ***box*** to indicate that the condition corresponded to the ***box*** is holding.
(5) A ***gate arc*** connects a ***transition*** with a signal source, and depending on the signal, it permits or inhibits the occurrence of the event that corresponds to the connected ***transition***. ***Gate arcs*** are classified into enabling or inhibitor, and internal or external.
(6) An ***output signal arc*** transmits a flag from a ***box*** to an external element of the graph. The value of signal is “1” when there is a mark in the ***box***, otherwise it is “0”.

The detailed definition of MFG and its extensions can be found in (Miyagi1996; Santos Filho 1998). An example of MFG model and its structural elements is shown in Fig. 4. Initially, the system is in stand-by condition, represented by a ***mark*** in the “stand by” ***box***.

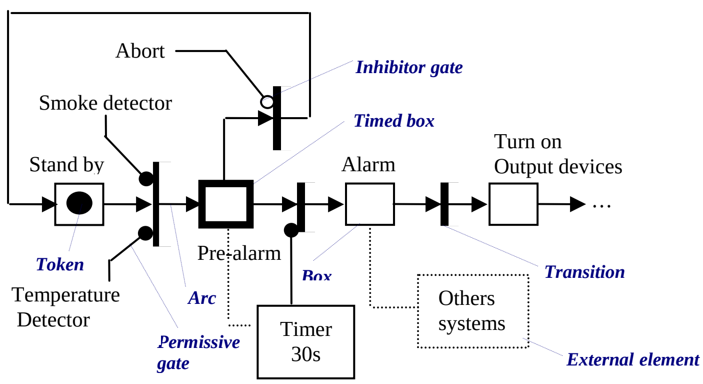

Figure 4. Example of MFG model and its structural elements.

When the system receives appropriate signals from the smoke sensor and temperature sensor devices, the pre-alarm procedure is started. This pre-alarm can be aborted up to 30s after beginning this procedure. After this time if the pre-alarm procedure is not aborted, the alarm procedure is activated; sending a signal to the other building systems and activating FPS output devices. If the system is aborted during the pre-alarm procedure, the system returns to stand by condition.

5. FPS Modeling Procedure

The procedure proposed for FPS modeling is composed of four steps, illustrated in Fig. 5 and detailed as follows:

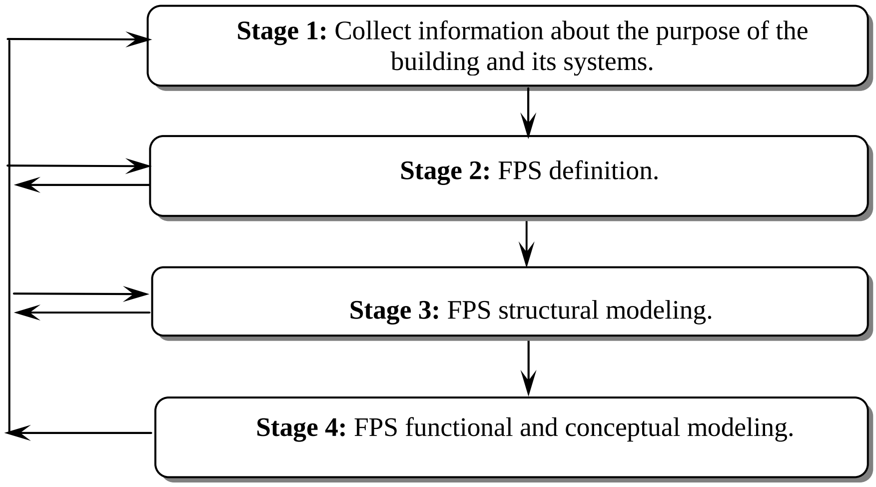

Figure 5. Methodology for FPS modeling.

Stage 1: Collect information about the purpose of the building and its systems.
This is the initial stage in FPS modeling. In this stage a research is carried out with the purpose of collecting information about the building. This information is used to perform a preliminary analysis and identification of relevant data for building a model. These data must characterize the building behavior in quantitative and qualitative levels. At this stage the standards related to firefight and protection must be considered to specify the FPS according to the building characteristics.

Stage 2: FPS definition.
In this stage, the information of Stage 1 is analyzed and the requirements of the FPS in the building are specified, considering the security standards related to it. The control procedures must also be defined. A careful evaluation and information analysis in this stage must be able to identify problems of interpretation in case of unclear, inconsistent or incorrect information, and also verify the needs of new researches.
In this stage, the following information is specified: (a) what are the necessary procedures to attend the standards; (b) what are the devices used in each procedure; (c) the input and output of each procedure.

Stage 3: FPS structural modeling.
This stage consists of developing the FPS structural model. The devices and sub-systems that compose it are identified, considering the IB context and also the control system architecture. Basically, the FPS is represented by the interconnection of two important subsystems: the controlled object (protected zone) and the control system.
The information generated in this stage are: (a) FPS structural diagram, (b) identification of control devices; (c) identification of detection devices; (d) identification of actuation devices; (e) identification of monitoring devices; (f) identification of command devices. This information is the starting point to detail the system in stage four.

Stage 4: FPS functional and conceptual modeling.
In this stage, the modeling of each structural element is performed systematically according to a hierarchal approach. Initially, the system conceptual modeling is developed by gradually refining the models until its functional model is obtained. The FPS conceptual model is particularly important to deal with interpretations of the information obtained in the previous stages (which can be subjective). This model describes the system organization and allows a deep comprehension of different parts. Afterwards, the modeling of the interrelations and functions of its components results in an appropriated functional specification. In this stage the PFS/MFG methodology is adopted (Miyagi, et al., 1997). The functional model contains the description of the system dynamic behavior. The models are then analyzed in order to verify if they satisfy the specifications of the FPS in such way that its dynamic behavior should be equivalent to the expected behavior. The verification can be conducted by simulation technique and/or formal analysis of the MFG based on the Petri net properties (Peterson 1981; Murata 1989).

6. Example

Due to the limited space available just a sample of some results obtained in the developed stages are presented in this section. The example used to illustrate the proposed methodology is the FM-200 gas based FPS of the equipment room of the “Banco do Estado do Ceará” (BEC, 2004), located in Fortaleza, CE, Brazil. This building has some characteristics that indicate that IB concepts have been adopted in its design.

Stage 1: Collect information about the objective of the building and its systems involved.
This stage was developed reviewing the available documentation of the building. The FPS in this building uses FM-200 gas system due to the installed equipment and the activities of the bank. The FPS must be in accordance with the NFPA standards (NFPA-2001, 2004). The FPS is composed of particle sensors, multiply smoke, temperature detections and alarm control panel. A cylinder battery of FM-200 gas performs the automatic firefight. The gas, transmitted by pipes and diffused by nozzles, saturates the risk area eliminating any fire focus.

Stage 2: FPS definition.
According to ABNT (1998) and NFPA-2001 (2004), the main specifications for the FPS in this case are:

- The FM-200 gas system must allow automatic and manual discharge.
- The system must have two independent control nets, one monitoring smoke and temperature (multi sensors) and the other net monitoring the particle sensor, located in the ventilation ductwork of the HVAC.
- When the temperature sensor reaches 30ºC, the alarm control panel must initiate a pre-alarm procedure, without initiate the event sequence that activates the FPS.
- The activation of the fire extinction system can be aborted until 30s after beginning of the pre alarm procedure.
- In case that the temperature sensor reaches 60ºC or more and/or 30s after the pre-alarm activation, the FM-200 fire extinction system is activated with no possibilities to be aborted.
- The system must send a signal to the control solenoid valves of the gas cylinder and automatically open the cylinder valves after confirmation of fire.

Stage 3: FPS Structural modeling.
This stage identifies the components of the FPS in two groups, those that belong to the control system and others that belong to the controlled object. The controlled object in this example includes the air in the risky area. The purpose is to control air characteristics such as temperature and amount of smoke. Table 1 shows the control devices.

Table 1. Control devices

Classification	Devices
Manual commands	Manual fire alarm station, abort station for extinction system
Direct sensors	Smoke sensor, temperature sensor
Indirect sensors	Particle sensor
Actuation devices	Solenoid valve, HVAC dampers
Monitoring devices	Warning luminous alarm, addressable audiovisuals alarm
Achievement device	Alarm control panel

Stage 4: FPS functional and conceptual modeling
The FPS functional and conceptual models are developed according to the information and system definition. Therefore the conceptual modeling considers each one of the structural system elements in a top down approach. This modeling is performed using the PFS, MFG and its extensions.

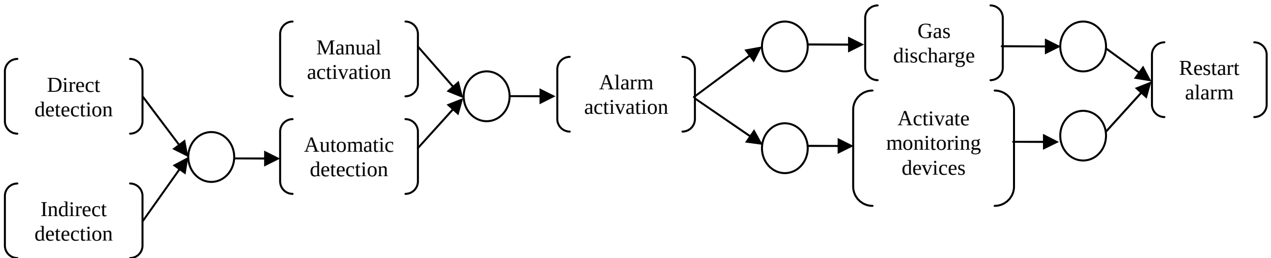

Figure 6. Example of PFS model of one of the FPS procedures.

Fig. 6 presents the PFS model of one of the FPS procedures. In this model, the “alarm activation” can be initiated by manual activation or automatic detection. The alarm control panel activates the monitoring devices and gas discharge simultaneously. The activity “automatic detection” receives the input signal from the “direct detection” activity or “indirect detection” activity.

Fig. 7 describes the dynamic behavior of “direct detection” activity developed in MFG. In this activity, sensors constantly measure the temperature of the environment and the presence of smoke. In “indirect detection” activity (see

Fig. 8.a.), the particle sensor constantly monitors the airflow in the building ductwork. The "manual activation" (see Fig. 8.b.) transmits the information of an initial fire or emergency situation from the manual station when activated by the human element.

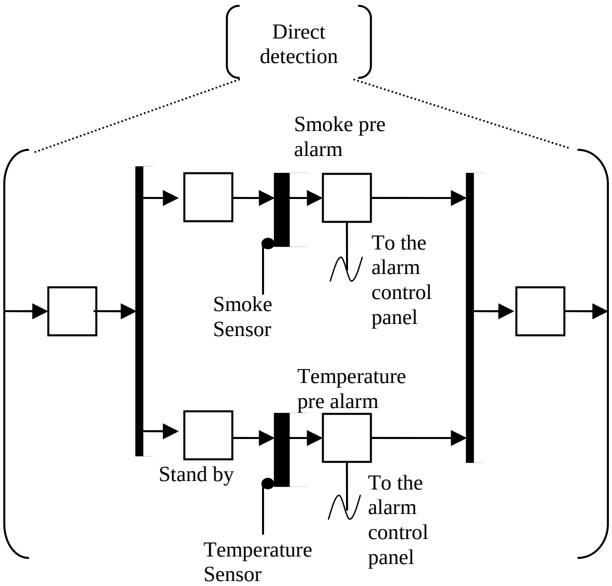

Figure 7. MFG Model of the activity "direct detection".

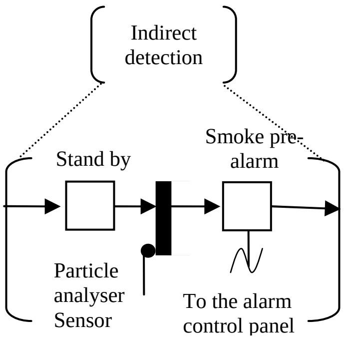

Figure 8a. MFG Model of
the activity "Indirect detection".

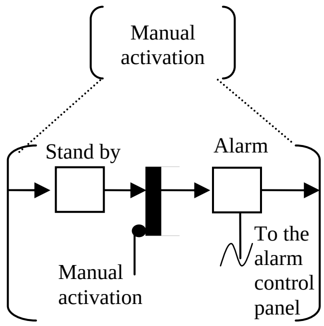

Figure 8b. MFG Model of
the activity "Manual activation".

The "automatic detection" activity receives signals coming from direct detection and indirect detection devices (see Table 1). In this activity, the pre-alarm procedures are started in two cases: (a) when the temperature sensor reaches 30°C or (b) when the smoke sensor is activated and the particle sensor detects smoke presence in the HVAC air ductwork. This pre-alarm can be aborted using the abort station device until 30s after beginning of the pre-alarm procedure. After the gas discharge and monitoring devices are deactivated, the alarm system is restarted manually.

After construction of the FPS model, it should be verified and validated. In the present case, the software HPSim (Anschuetz, 2001) is used to analyze by simulation the resulting models.

7. Conclusions

This paper introduces a procedure for the modeling of FPS. The FPS is considered as Discrete Events Dynamic System and the proposed procedure is based on interpreted Petri net. This procedure allows the structured development of models, facilitating the modeling process and upgrading of FPS specification.

The example of Section 6 illustrates the following features of the proposed methodology:

- It is a systematic approach for the construction of models that can be used for verification and validation of the system.
- It identifies the system characteristics and operations in a unambiguous and clear way;
- It describes the system from conceptual to detailed level according to the hierarchical structure of the systems activities, considering aspects such as modularity, flexibility and expansion capability.

However the effective integration with other building systems include the manipulation of a greater number of variables and different type of signals and therefore, additional investigations should be conducted. Works such as

Bastidas et al. (2003) indicate that object oriented concept and open and distributed control system plays an important role in the design of supervisory functions in Intelligent Buildings. On the other hand, the studies about the fire and human behavior in emergency situations (Villani; Kaneshiro; Miyagi, 2005) indicate that hybrid system concept and uncertainties are also important in the definition of the strategies for fire management in buildings. Then, in the future the aim is to improve the present work and propose a general design procedure of supervisory systems to intelligent building considering the problems and solutions above mentioned.

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