

PROCESS MODELING AND FAULT DIAGNOSIS OF FLEXIBLE ASSEMBLY SYSTEMS USING PETRI NET

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Abstract. *A significant part of the activities in a manufacturing system involve assembly tasks. Nowadays, these tasks are object of automation due to the market increasing demand for quality and variety of products. Them, assembly system automation must be also flexible to cope product diversification, functionality, delivery time and volumes involved. However, these are vulnerable to faults due to the physical characteristic systems of their components and the complex interaction among their parts. In this context, current researches are focused on the project and control of Flexible Assembly Systems (FAS) considering the occurrence of faults. The proposed procedure structures the development of models assembly process and the fault diagnosis, based on the theory for Discrete Events Systems (DES) and Petri net (PN). The Production Flow Schema/Mark Flow Graph (PFS/MFG) technique is then applied to describe and specify the FAS control system through a rational and systematic procedure.*

Keywords: *Flexible Assembly Systems, Discrete Event System, Petri net, PFS/MFG*

1. Introduction

A Discrete Event System (DES) is a dynamic system and its evolution is produced by abrupt changes of discrete states as result of the occurrence of physical events. For example, an event may correspond to the movement of a workpiece in a transport system, the occurrence of a disturbances or the change in the set point in the control system. DES is applied on domains such as manufacture, robotic, traffic control, logistics, and communication. These applications require control and coordination to organize the flow of items (information and material) and the occurrence of events (Ramadge and Wonham, 1989).

A Flexible Assembly System (FAS) can be modeled as a DES that contains activities such as part setup, workpiece transfer, tool exchange, and part assembly. Each activity has at least one start event, one ending event and one internal state that can be composed by sub-activities. The design of an assembly system is not trivial and deal with technical problems due the countless functional aspect to be considered (Nevins and Whitney, 1989). The designer's experience is a crucial portion of the available information about the assembly process. Relevant information is evidently also related with the product and its parts, provided by suppliers, the assembly operations, resources, and facilities. Therefore, the design of a FAS can directly affect the manufacturing costs. The complexity of design processes require the use of computer-aided tools to assist the making decisions during the system modeling and analyzing process. In a conventional assembly system design, designers make the decisions at early stages of the development cycle, then individual parts of the system are designed independently with low interaction, sometimes disconsidering the assembly process, and the existence of resources due to the lack of an integrated approach (Zha; Du and Lim, 2001).

The elementary components of a FAS such as sensors and actuators are subjected to unexpected faults, witch produce unacceptable deviations from nominal conditions (Alcorta-García and Saucedo-Flores, 2003).

Thereby, the purpose of this work is to propose a rational and systematic approach for FAS design. This paper initially presents an overview of the main concepts related to FAS. Section 3 shows a technique derivate from Petri net and adapted for the FAS representation. Section 4 presents some concepts relevant to fault diagnosis and the proposed modeling procedure. In section 5, an example of application is presented which introduce the proposed approach. Finally, in section 6, some comments and conclusions are presented.

2. Flexible Assembly System - FAS

Before discussing the design of FAS it is important to understand the limitations of conventional dedicated assembly systems. Dedicated assembly system is a mass production technology developed in order to produce a large number of a single workpiece or product. The assembly task in this context is divided in simple operations where each one can be automated, and them be connected by a transport system (Sawik, 2004).

A FAS is a network of production cells interlinked by a transport system. Each cell consists of one or more workstations, and each workstation has a workspace for part feeders, input and output magazines with finite capacity for temporary storage of parts waiting for processing or for transferring to other workstations. Physical capacity of in-process magazines helps to limit the average work-in-process and maintain the material flow in the FAS.

Different types of tasks can be performed in the FAS to assemble various types of products. Each product passes through a subset of workstations, where the required part feeders has been assigned (Hopp and Spearman, 1996).

The development of FAS involves the design, selection, and integration of a number of different mechanical systems in order to develop a flexible assembly facility, capable to assemble a wide variety of products. A specific system configuration is dependent on a variety of factors such as: product size, part material, available tools, available grippers, etc. (Edmondson and Redford, 2002).

3. PFS/MFG for FAS representation

In this section, a brief introduction to PFS/MFG (Production Flow Schema/Mark Flow Graph) is given. The definitions here are based on (Miyagi, 1996); (Santos Filho et al., 2001).

The modeling of FAS has been recognized as a stage of the system design this is fundamental to assure an efficient assembly in a production environment that demands tasks with a high degree of flexibility. The principle of the proposed approach is based on the PFS/MFG technique. The PFS/MFG technique is derived from Petri net (PN) formalism. It is an interpretation of PN structure applied on manufacturing systems control. In the present case, the assembly systems are modeled by adopting the PFS/MFG to represent the system structure and its dynamic behavior.

A conceptual model in PFS can be developed for FAS functional specification. In a conceptual model, the aim is to identify the relationship among activities in a system where the structure and the dynamic-behavior is based on the flow of items (information and material). The resulting model in PFS can be refined step by step into a control model through MFG, i.e., the control solution adopted to the problem. From the MFG, the analysis of the model system is performed analysis of the modeled system. The formal analysis explores all properties and tools developed for PN.

The PFS/MFG technique is concerned with the task of modeling applying a top-down approach. The systems can be modeled through the PFS/MFG technique and be analyzed adopting a hierarchy for the dynamic behavior system. The PFS/MFG models these behaviors in accordance with the desired abstraction level. Figure 1 illustrates the FAS hierarchy where the model representing the processes in each level of the system is introduced.

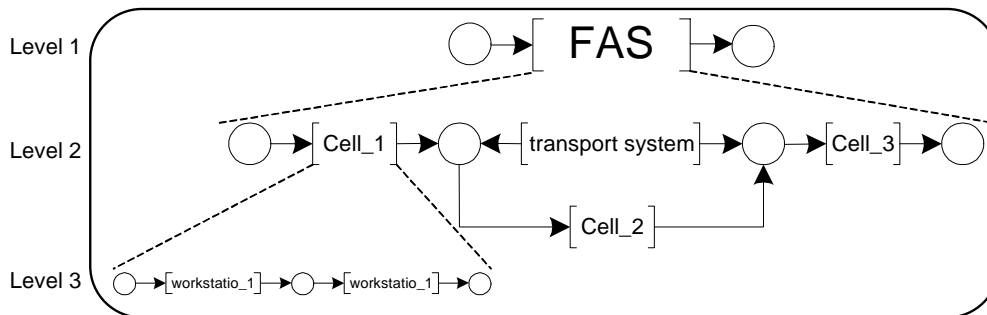


Figure 1. Hierarchical modeling process of a FAS applying PFS/MFG

4. FAS modeling and fault diagnosis procedure

Based on the automation degree of a FAS, two types of fault detection can be considered (Miyagi and Riascos, 2005):

- Fault detection by monitoring a specific device parameter. For example, the overflow or absence of workpieces in the magazine can be detected by installing a sensor, which monitors this condition.
- Fault that cannot be detected directly from the monitoring process. Such faults need some type of diagnosis.

This work focuses on faults of the second type. In general, fault diagnosis methods can be grouped into two categories (Dash and Venkatasubramanian, 2000):

- Process model-based: this method consider a set of relations that describe the interactions among various process variables.
- Process history-based: this method make use of the large amount of process-history data.

Process history-based method can also be further subdivided into *qualitative* methods and *quantitative* methods (Power and Bahri, 2004). The method described in this work adopts the idea of using dynamic fault data in order to diagnose faults as described by Vaidyanathan and Venkatasubramanian (1992).

The fault diagnosis has mainly focused on steady state data when they are already occurred. This is clearly an approach that considers an existing FAS, where faults are detected as soon as they occur. In addition, it is hard to distinguish the root cause of the fault because the fault can propagate throughout the FAS. The fault detection and diagnosis module described in this work detects the faults in their initial phase and thus will be referred diagnosis of incipient faults.

The method proposed for system modeling and fault diagnosis procedures is based on the application of the PFS/MFG technique. In the proposed method, three stages are considered for the system modeling and one stage is considered for the fault diagnosis procedures:

- **Detailing the process:** this stage is used to detail and to identified the normal evolution of the assembly process and then to model it through the PFS technique.
- **Signals definition:** this stage generates a set of tables to help the designer to identify the function of the actuators and sensor of the FAS.
- **Detailing the control device:** in this stage the functions of the FAS control systems are detailed with MFG, FAS signal detection are represented with *inhibitor* and/or *enabling gates* from *external element* to *transitions* of the model, and actuator signals are represented with *signal output arc* from *boxes* of the model to *external elements* (Miyagi, 1996).
- **Fault diagnosis:** The fault detection (step one) and diagnosis (step two) framework is presented in Figure 2. The MFG detection module detects the fault based on dynamic data, i.e., identify the mark possessing fault. This MFG then directs the diagnosis to the PFS model for the functional flow, i.e., locate the fault. This detection and diagnosis methodology allows the isolation of the root cause and the diagnosis of the fault.

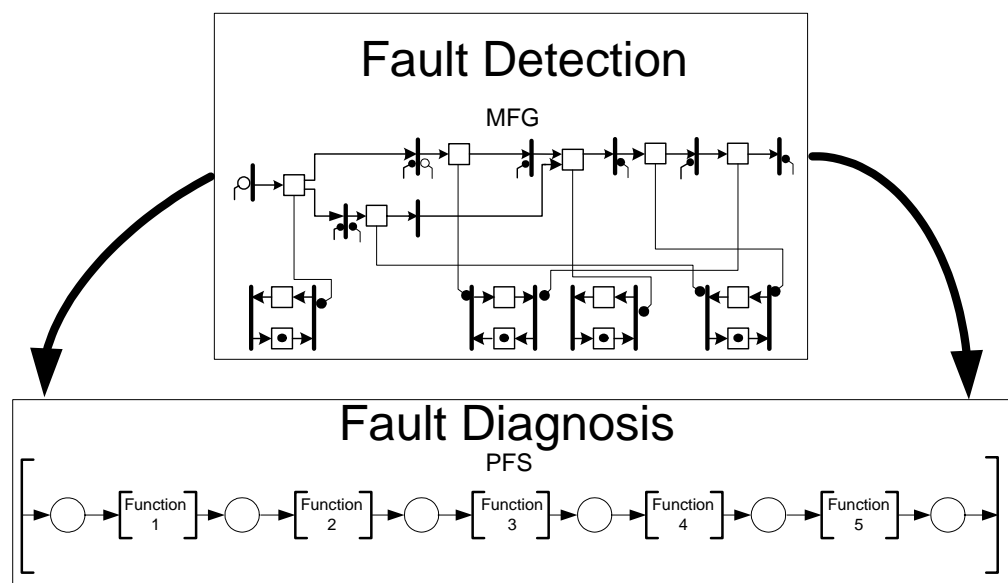


Figure 2. Fault detection and fault diagnosis models.

5. An application example

To illustrate the use of the proposed FAS modeling procedure, it was applied to an existing system (Figure 3). This FAS comprises 3 production cells: material input cell (I), assembly cell (A), warehouse cell (W), and one transport system (T).

- The material input cell (I) consist of a supply workstation (Su) and a testing workstation (Te);
- The assembly cell (A) consist of an assembly workstation (As) and robot workstation (Ro);
- The warehouse cell (W) consist of a handling workstation (Ha).

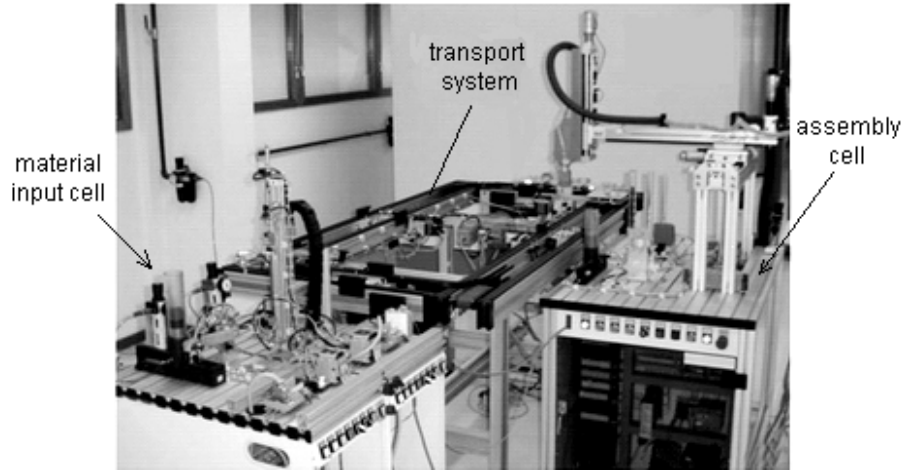


Figure 3. An example of FAS

The FAS transport system has 3 working positions related to each production cell and it has sensors for pallet identification. Figure 4 shows the FAS functional architecture with its cells, workstations, and the transport system.

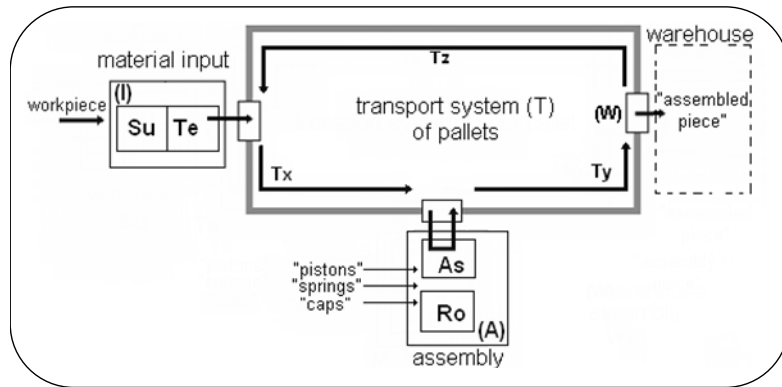


Figure 4. Production cells and the transport system of the FAS shows in Fig.3

5.1. FAS process

The main activities of the FAS are identified through the PFS model. In this model, activities, sequences, and the materials flow are explicitly represented (Figure 5).

The supply workstation receives red, black, and silver workpieces. Up to ten workpieces are stored in the stacking magazine. A double-acting cylinder pushes the workpiece out one at a time. A feeder arm gets the separated workpiece via a suction gripper. This feeder arm moves the workpiece to the transfer point of the testing workstation (Te).

The testing workstation (Te) detects the attributes of the workpieces inserted into it. It differentiates the workpieces through an optical, an inductive, and a capacitive sensor. A retro-reflective sensor monitors whether the operating space is free before the workpiece is raised via a linear cylinder. A comparison sensor measures the height of the workpiece. A linear cylinder pushes the approved workpieces to a pallet on the transport system. Faulty workpieces are rejected.

The PFS models are then detailed to characterize the internal processes of each production cells. Figure 6 shows the PFS model of the material input cell (I) and detail of workstation (Su).

The assembly workstation (As) works in conjunction with the robot workstation (Ro). It supplies "pistons" "caps" and "springs" components to the assembly process. The robot workstation (Ro) can transport pallets that are fed via the transport system (T) to the assembly workstation, and then transport the workpiece to the temporary retention device. From the temporary retention device the robot assembly the components stored in various magazines.

The handling workstation (Ha) is equipped with a flexible two-axis handling device. The handling picks the assembled piece up from the warehouse through a pneumatic gripper. The gripper is equipped with an optical sensor that differentiates between "black" and "non-black" assembled piece. The assembled pieces can be placed on different storages according to this criterion.

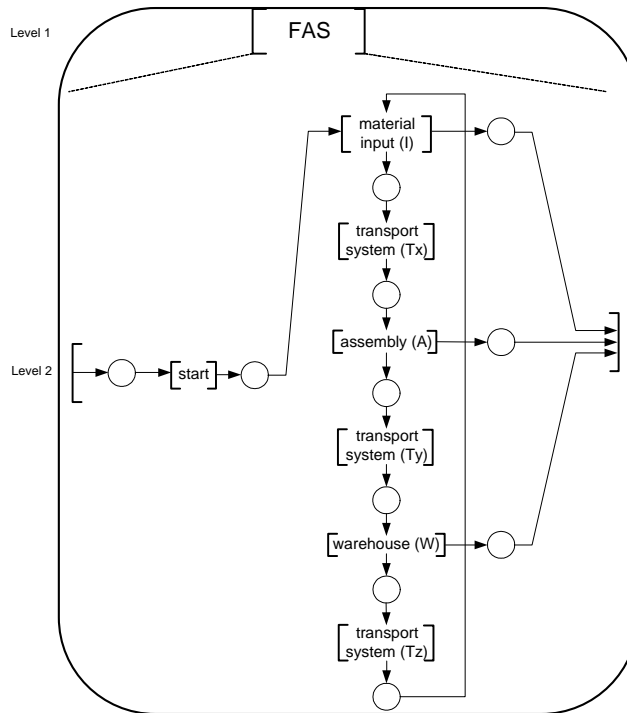


Figure 5. Main activities of the FAS

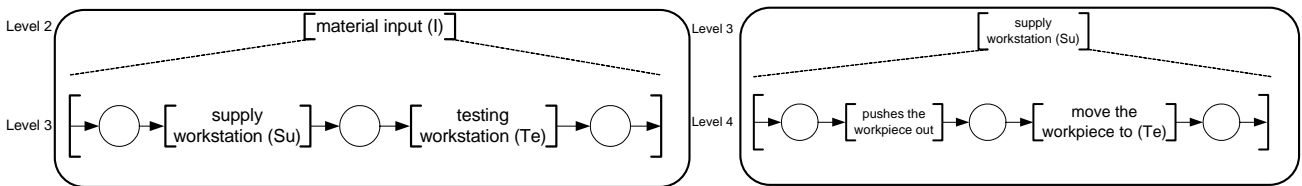


Figure 6. PFS model of material input cell (I) and detail of supply workstation (Su)

Due to limitation of the paper, only the supply workstation (Su) will be detailed. In Figures 7 and 8 the functions of the supply workstation (Su) through PFS/MFG technique are illustrated. The MFG technique model the functional interaction with the detector and actuator devices.

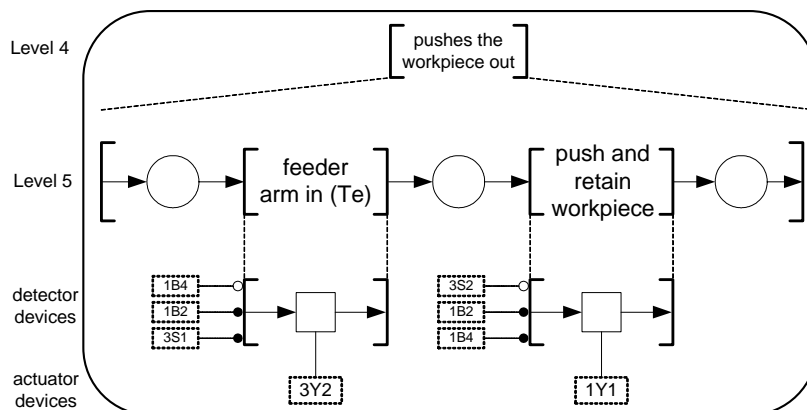


Figure 7. PFS/MFG model of workstation (Su)

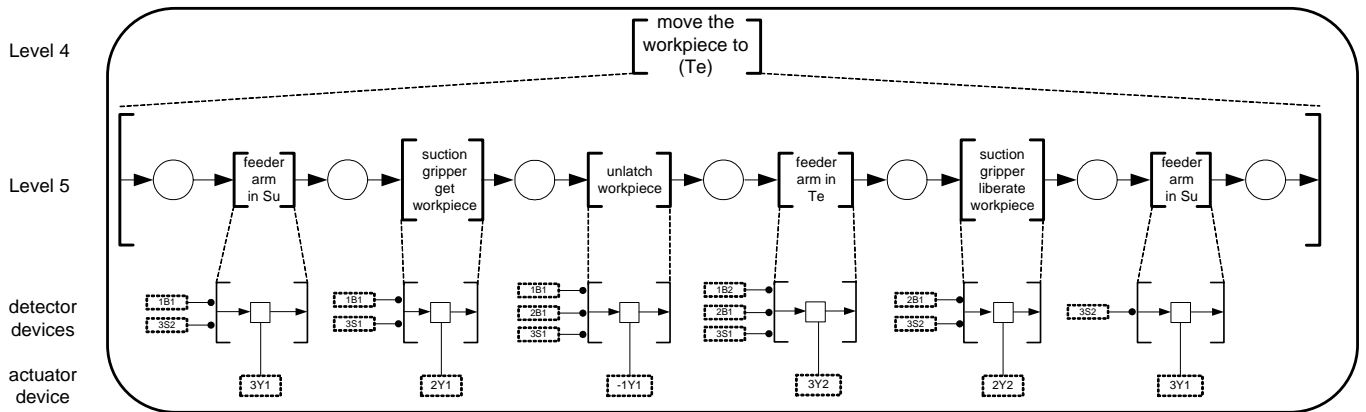


Figure 8. PFS/MFG model of workstation (Su)

5.2. Signals definition

In order to illustrate the considered method, only the supply workstation (Su) is considered. Tables 1 and 2 show the proper primitives to perform the communication task. They use a nomenclature for actuators and sensor devices, based on the DIN/ISO 1219-2 specification. For example, in the nomenclature 1 S 2; 1=circuit number, S=device code, and 2=device number. The device code is recommended by IEC 61346-2. The tables were elaborated accordingly to the (Su) internal process details and operational specifications.

Table 1. Summary of actuator devices

nomenclature	function	actuator type
1Y1	It modifies the state of the valve-1 for piston retreating position	solenoid
2Y1	It modifies the state of the valve-2 for vacuum generator that activate position	solenoid
2Y2	It modifies the state of the valve-2 for vacuum generator that deactivate position	solenoid
3Y1	It modifies the state of the valve-3 for swivel arm in supply workstation	solenoid
3Y2	It modifies the state of the valve-4 for swivel arm in testing workstation	solenoid

Table 2. Summary of detector devices

nomenclature	function	detector type
1B1	It detects the piston retreat position	magnetic proximity sensor
1B2	It detects the piston extended position	magnetic proximity sensor
2B1	It detects if the suction gripper caught a workpiece	vacuum sensor
3S1	It detects if the swivel arm is in the testing workstation position	electrical switches limit
3S2	It detects if the swivel arm is in the supply workstation position	electrical switches limit
1B4	It detects the lack of the workpiece in the magazine	optical sensor

5.3. Detailing the control device

The PFS/MFG model is then detailed in order to consider the interfaces between actuators and detection devices. A simulation tool, the HPSim (2001), is used to verify the models. The tool can simultaneously simulate several PN with linked procedures. The tool has graphic resources. Elements (such as circle=*boxes*, bars=*transitions* and arcs=*gates*) are edited by a “click” of the mouse, and dialog boxes permit it to define properties and specifications of simulation. The tool was developed for MS-Windows so as to use a friendly and well-known environment. Figure 9 shows a hard copy of the simulator with the supply workstation (Su) model.

5.4 Fault diagnosis

Several researchers prove that fault diagnosis in assembly systems can be structured in an automatic way (Dornfeld, 1990). Accordingly with process history-based method, the measured signals are considered in the detecting process (signals to external element) and the estimation of the nominal values of signals output. This step defines the marking of the MFG model in Figure 9. Figure 10 (a) shows the initial marking of the supply workstation (Su) model.

In Figure 10 (b) the fault occurrence in the assembly process is detected (identified) and the Figure 10 (c) shows the fault diagnosis (identification and localization) in the supply workstation (Su) for the functional flows by PFS technique.

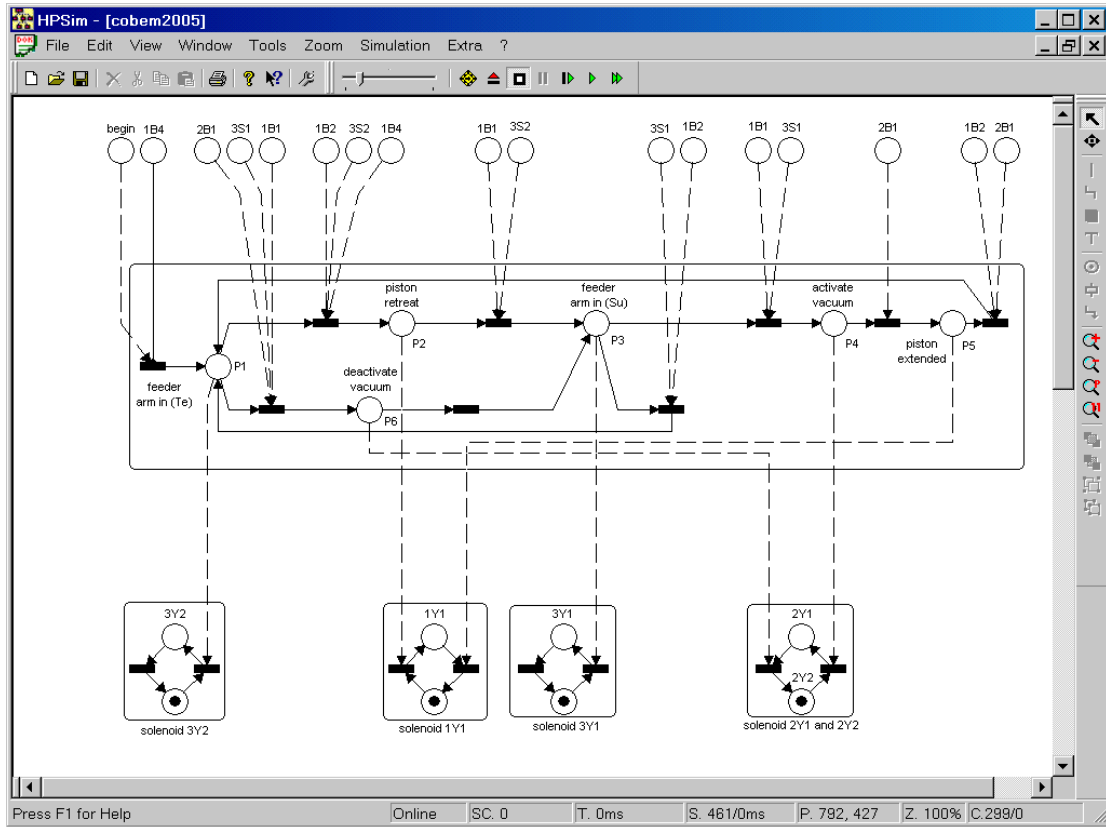
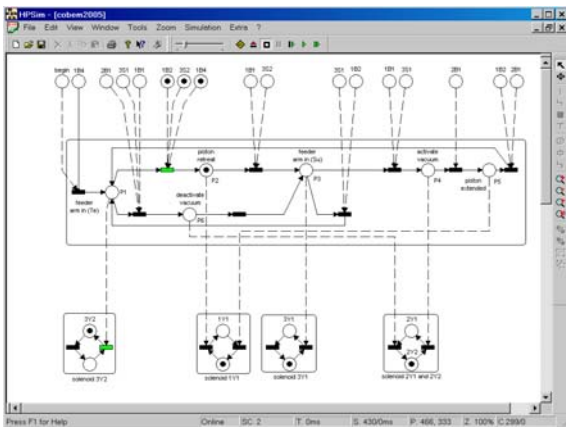
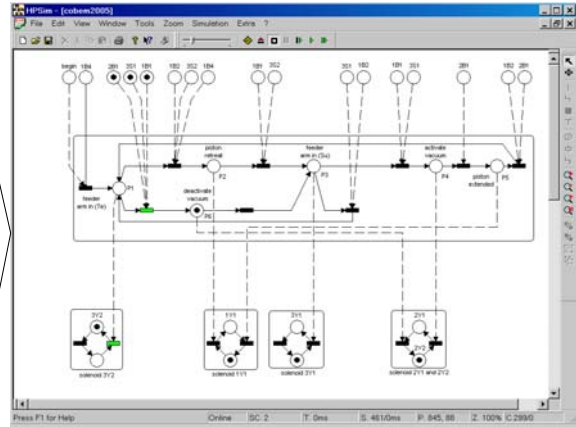


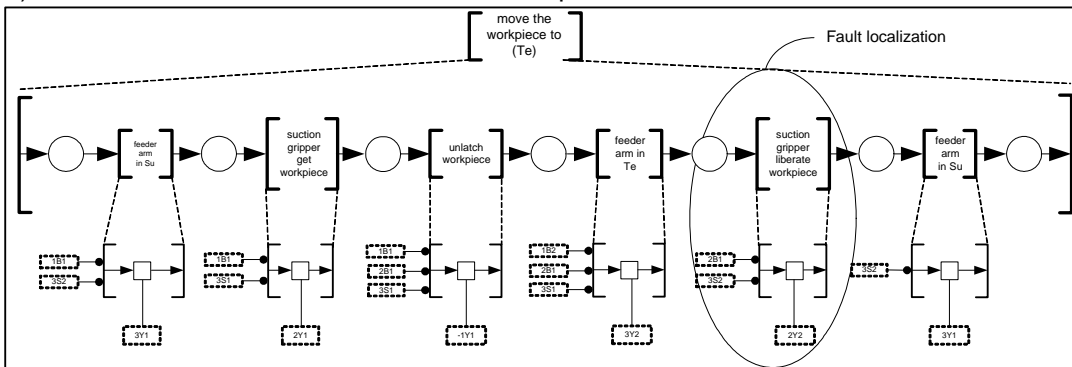
Figure 9. MFG model of the supply workstation (Su)



a). Nominal model simulation with MFG technique



b). Model with fault detected



c). Fault diagnosis in PFS model

Figure 10. Fault detection and diagnosis with PFS/MFG

6. Conclusions

This paper proposes an approach for modeling Flexible Assembly Systems (FAS). This approach is based in the discrete event system theory and in the use of Petri net. It presents a hierarchical approach that guides the designer from conceptual activities to detailing process.

This paper also considers the detection and diagnosis of faults in assembly systems, special the method based on the process history. This method is applied with Petri net model of the FAS.

Works such as (Miyagi and Riascos, 2005) indicates that the Behavior Petri net (BPN) approach can also performs an important role in the design, detection, and treatment of faults in Flexible Manufacturing Systems (FMS). Future works may consider this approach to improve the procedures of fault recovery.

This technique was applied to an example and revealed efficient in the detection and diagnosis of faults as well as in the identification of the device that generated it.

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8. Responsibility notice

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