Integrated design, scheduling and automation of a production process using Petri Nets

I.A. ANTONIADIS, Assist. Professor
Mechanical Eng. Dept., Machine Design and Control Systems Section
National Technical University of Athens
15780 Zografos
GREECE
Tel: +301 7721524, Fax: +301 7721517

V.I.N. LEOPOULOS
Lecturer
Mechanical Eng. Dept., Industrial Management & O.R. Section
National Technical University of Athens
15780 Zografos
GREECE
Tel: +301 7723585, Fax: +301 7723571

Abstract: In traditional industrial practice, the tasks of production planning and control and of automation design and implementation are performed in the same industry at different levels by different departments or teams, using quite different, application specific conceptual and programming tools (e.g. IDEF-0 in the production planning, STL, LAD, or SCL in the automation area, etc).This paper proposes the integrated application of Petri-nets for the whole spectrum of the above activities, demonstrating this approach in a case study in the consumer goods industry. The use of the same model for the design of the production system and the automation system facilitates largely the communication, not only between the experts but also between the information tools used, reducing radicaly the design, installation and re-engineering time and increasing the flexibility and modularity of the system.

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1. Introduction

1.1. Initial conditions and problems

The markets' requirements for sophisticated high quality products in small amounts and quick response to the demand necessitate production systems with high flexibility. At the shop floor level production is organised in multi-product production lines and the minimisation of the response time is faced by incorporating the production planning to the production systems' design [7]. In order to increase flexibility, simple and smart automation systems attached to traditional equipment replace the expensive complicated automated machines [9].

Although these problems are closely connected the modelling techniques used are different mainly for historical reasons. The techniques of SPIF (Systematic Planning of Industrial Facilities) type, have been developed for the design of production systems which will be expanded in the future but without frequent re-arrangement of the equipment [5].

An additional problem is the capacity utilisation. The concept is well defined in the hybrid batch/continuous flow process as in the soap producing factory [8]. The capacity of any piece of equipment (mixer, mill, press, pack) is known because every piece has been engineered taking into consideration all the continuous flow, and the current capacity is also easily measured. Moreover because the plant's designers want to leave as little waste or unused capacity as possible, the capacity utilisation for any single piece of equipment is often very close to the capacity utilisation figure for the process itself. Since the process's capacity utilisation is determined by the bottleneck operation, the equipment capacities are likely to lie close to the bottleneck capacity. The high degree of capital intensity dictate concern for the selection of proper technology and the balancing of capacities in all segments in process. Over time rearrangement of the existing equipment or technological advance has dictated numerous advances in the process itself and in the scale of the process. The design, choice, and matching of equipment are critical decisions for the soap production.

Simulation is often used to evaluate the functional specification of a manufacturing system on the physical level. The modelling tool is either a classical computer language, or a simulation language, the latter being much more helpful for common applications. Various mathematical approaches are also available.

Similar problems exist in the area of automation systems programming, simulation and evaluation. Several languages are used for PLC programming, such as Statement List (STL), Ladder programming (LAD) or function block diagrams (FBD). Although several attempts have been made to bring them to common standards, still many incompatibilities exist between equipment vendors. More over, their concepts and structure are quite different than those used in the production planning and control.

1.2. Objectives and methodology

A model is developed at different levels, ranging from major process activities to the fine details of the automation of the process. The modeling approach followed, proposes three different levels/models:

A. The production system level model
B. The detailed physical system model
C. The detailed automation system model

Each one is constructed with its corresponding Petri-net, in close cooperation with the others. Each model is constructed with appropriate combined modules.

The model is used to test different production designs for different production schedules, performing qualitative or quantitative analysis. Qualitative analysis checks the absence of deadlocks or overflows, the presence of certain mutual exclusions in the use of shared resources, etc. Quantitative analysis looks for performance, responsiveness and utilisation properties. In both cases, data resulting from the detailed automation model, such as real machinery performance or possible faults, are taken into account, contributing to a full and realistic analysis. Furthermore, the model is used for the development of the programming code of the several PLCs involved in the automation of the process, as well as for its simulation and evaluation.

1.3. Structure

The paper is organised as follows: In Section 2, the case study is presented. In Section 3, the production system level model is presented as a Petri-Net using the ARTIFEX tool [1]. In Section 4, the detailed physical system model is presented, using interpreted Petri Nets. It includes the detailed automation system model and the detailed physical system model. In Section 5, the conclusions are presented and opportunities are identified for further research in this area.

2. The case study

2.1. The company

The company under consideration is a vertically integrated oleochemical industrial company producing and selling in Greece and in foreign markets:

- Cosmetics, toiletries; Soap (production capacity 10.000 ton/year);
- Edible oils (production capacity 6.000 ton/year);
- Fats: stearic acids, glycerines, oleines (production capacity 6.500 ton/year) and
- soft drinks

The company has a factory in Athens and two warehouses in Athens and Thessaloniki. The production units of the factory in Athens are presented in Figure 1.

2.2. Reapproaching the commercial and manufacturing policy

The neccessity to reaproach the commercial and manufacturing policy came from the prevailing market condition in the decade of 1990 namely:

- Drop of the national consumption in volume in the traditional product categories of the company and especially in bar soap;
- Drastic differentiation of the retailing business of fast moving goods resulting in the concentration of the bigger part of the market to a few big customers (super-market chains);

In addition the competitors approach consisting in:

- Negligible to nil price increase from all the main competitors
- Increase of the competition in the shops

Resulted in a change of the overall commercial policy in all the product's categories.

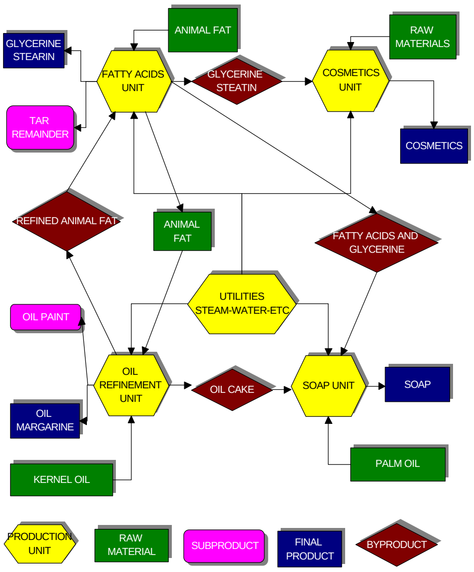


Figure 1. Production units of the test case considered

Apart from distributing their *own brand products*, the company act as *subcontractor* to a large multinational firm and produces *"private label products"* for large super markets, shipping companies, hotels, etc.

In combination with a continious decrease of the Administrative and Selling Expenses in relation to the total sales, due to a BPR operation an increased revenue was achived dispite the «adverse» conditions of the market.

While the production and distribution of own products can easily be forecasted and planned, the main problems in production planning come from sporadic customer orders in the form of foreign market contracts, private label products and one-off subcontracting for temporary customers. Each one of these customer orders has specific packaging requirements and irregularity in demand, which creates significant problems to the *production/marketing* interface. Usually there is difficulty in assigning a reliable delivery date, in pre-calculating customer order costs, in purchasing raw materials and in capacity planning.

A new the manufacturing strategy was thus necessary concerning the core activities of the production. The management examined the value-chain practices and techniques utilised for achieving improved business results, through focused improvements in core manufacturing processes, implementing lean, just-in-time philosophies and systems, eliminating waste, and achieving zero defects, while continuously improving products and costs.

In order to cope with the irregularity of the demand rearrangement of the equipment creates flexible production lines suited for the actual customer orders. As a result the problem of production line balancing and the connection with the automation systems, in the past faced once in a while, became critical. In addition to the experience of the production managers a technique was necessary to evaluate the performance of every new arrangement of the equipment.

3. Integration of enterprise models

3.1. The production system level model

The soap production system is modelled using modules which model a mixing machine, a mono-operational machine and a transportation system [3] [4], [6].

The production steps are briefly presented in

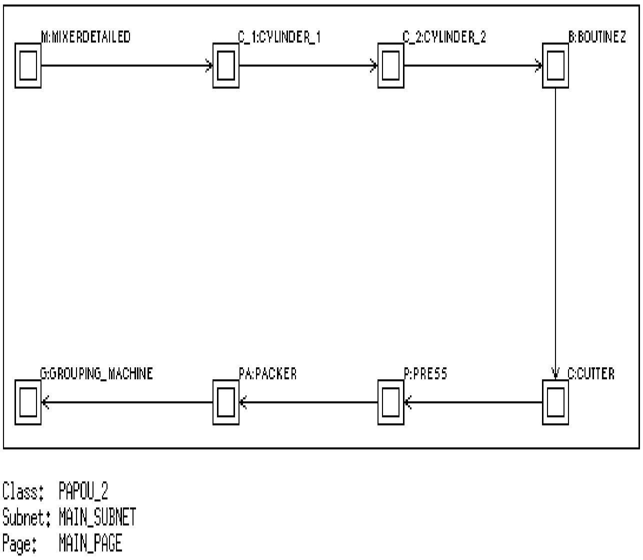


Figure 2:

Figure 2. Soap production – the steps of the continuous process

The quantities of soap mass, fragrance and colour are weighed and moved in a mixer through pipelines and other transportation systems. The soap after the mixing is moved in two cylinder where is milled for homogenisation. The soap is further moved into a machine that gives to the mass the form of a thin continuous soap bar. A conveyor belt moves the bar to the cutting machine where the bar is cut in pieces (soap bars) of 500gr.

The soap bars are further moved in the soap press where they are stamped and take the final shape. The press seals are cooled in order to remove easily the soap.

Finally the soaps are packed with polyester and paper and palletised in the grouping machine.

3.1.1. Material transportation and mixing

The model for the mixing follows the module for a mixing machine is shown in Figure 3.

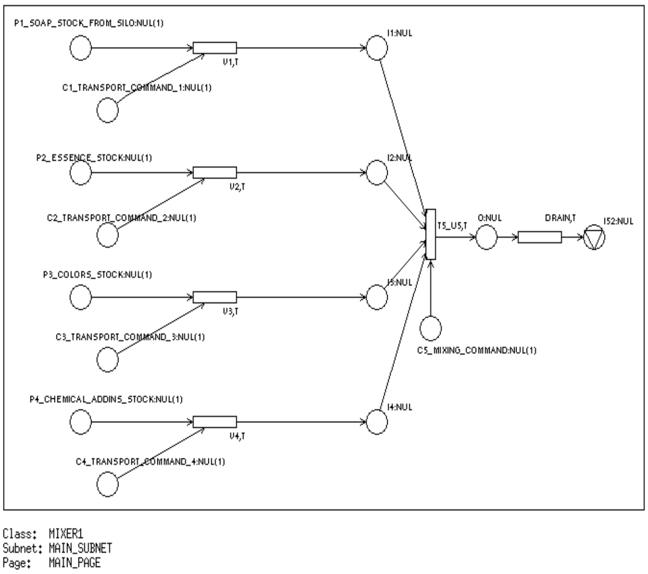


Figure 3. Mixing machine model

A token in the input place P1 (respectively P2, P3, P4) models the soap mass available in the silo (respectively fragrance, colour and chemical). The firing of the transition V1 (respectively V2, V3, V4) models the transportation order from the stock via the transportation system.

A firing time t1 (respectively t2, t3, t4) is assigned at the transition V1 (respectively V2, V3, V4). It models the necessary time for the transportation of the materials from the silo and the other stock areas to the mixer. A token in the place I1 (respectively I2, I3, I4) when the firing of the transition V1 (respectively V2, V3, V4) models the material available in the mixer.

If there is a token in the place C5_Mixing_Command then the transition T5 fires and a token appears in the place O after t5 time units. It corresponds in the production of one batch in the mixer. The firing of the transition DRAIN models the transportation of the batch to the next production step.

4.The detailed system model

4.1. General Concepts

A special class of Petri-nets -the interpreted Petri nets-, has been appropriately evolved [2] to the Grafcet form, in order to design automation models for Programmable Logic Controllers (PLCs). Thus, the design of an interpreted P-net for the automation, under certain conditions, can automatically lead to a corresponding PLC program. Furthermore, this program can be evaluated off-line, using a more detailed physical model of the system, by appropriate ’’zooming’’ on specific areas of the production system model.

Thus, the construction of a more detailed system model is possible, incorporating:

A. The detailed system automation model
B. The detailed system physical model

Interpreted P-nets can use external events or logical conditions (Receptivities) as additional prerequisites to trigger the transitions and can associate the (boolean) marking of places to the enabling of certain actions. Thus, linking the Receptivities of the automation model to the Actions of the detailed physical model and vice-versa, a model for the detailed system behavior can be achieved. This methodology is shown with more details in the specific case study.

4.2. Description of the Installation

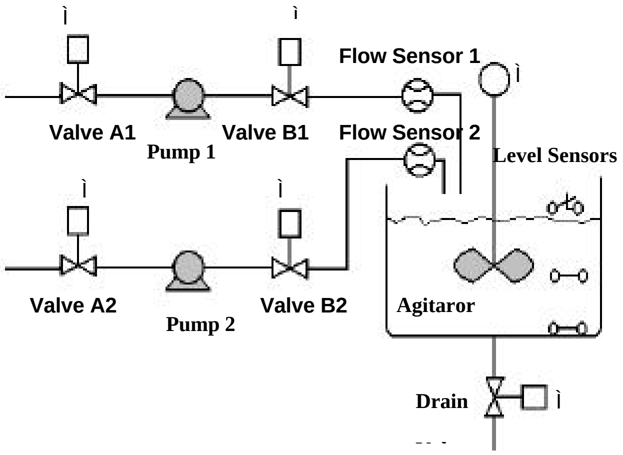


Figure 4: Simplified P&I diagram of the mixing installation.

The installation chosen for this purpose is the mixing process, previously described. The corresponding simplified P&I diagram is shown in Figure 4. In order to operate the system, an operator panel, shown in Figure 5 is used.

4.3 The detailed automation model

Since the equipment involved is quite common in the whole installation, general purpose modules (Interpreted P-nets) are used to define its automation. The requirements for the specific operation of this installation are inserted by appropriate conditions (’’interlocks’’) at the Receptivities and Actions of the general purpose modules. The inputs and outputs of the automation system are shown in Table 1.

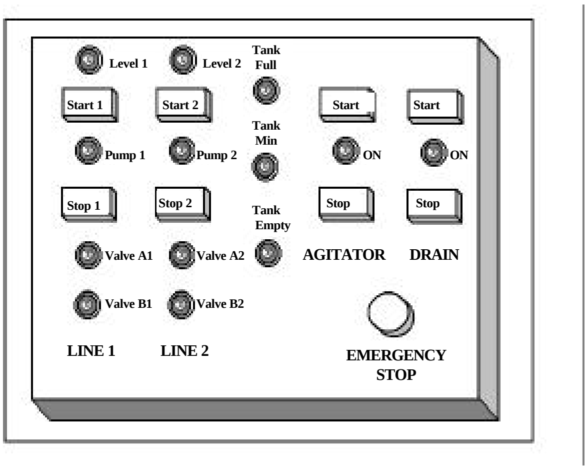


Figure 5. Operator panel used for the control of the mixing process.

4.3.1. General purpose modules

The two classes of general purpose equipment used in the automation are the motors and the valves. Two general purpose modules are used, as shown in Figure 6.

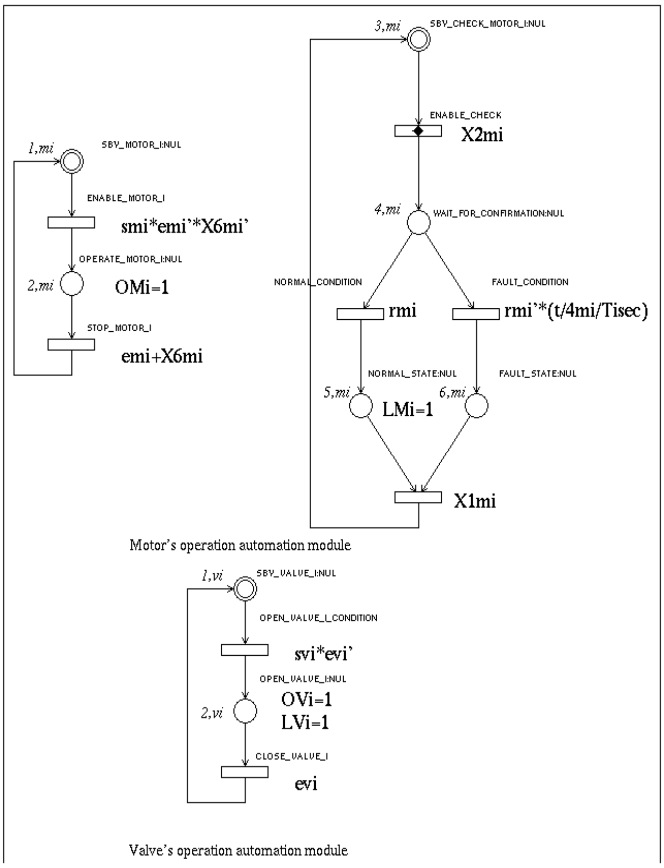


Figure 6. General purpose modules, used in the automation

es	Emergency Stop	**Lf**	Tank is Full
lm	Tank is not at Minimum level	**Le**	Tank is not empty
s1	Start Feeding by Line 1	**s2**	Start Feeding by Line 2
e1	Stop Feeding by Line 1	**e2**	Stop Feeding by Line 2
l1	Available material for Line 1	**l2**	Available material for Line 2
f1	Flow sensor for Line 1	**f2**	Flow sensor for Line 2
lt1	Level limit for Line 1	**lt2**	Level limit for Line 2
OM1	Operate pump 1	**OM2**	Operate pump 2
OVA1	Open valve A1	**OVA2**	Open valve A2
OVB1	Open valve B1	**OVB2**	Open valve B2
LP1	Indicate pump1 is ON	**LP2**	Indicate pump2 is ON
LVA1	Indicate valve A1 is Open	**LVA2**	Indicate valve A2 is Open
LVB1	Indicate valve B1 is Open	**LVB2**	Indicate valve B2 is Open
sA	Start Agitator	**SD**	Start opening Drain
eA	Stop Agitator	**Ed**	Start closing Drain
cA	Speed Monitor for Agitator	**OVD**	Open Drain Valve
OMA	Operate Agitator	**LVD**	Indicate Drain is Open
LA	Indicate Agitator is ON		

Table 1: Inputs and outputs of the automation model.

A. The motor module

Each motor can be in two different states {OFF,ON}, as shown in the corresponding steps {1,mi-2,mi}.They are activated by the ’’external’’ condition smi and deactivated by the ’’external’’ condition emi (multiplication denotes an AND condition, summation denotes an OR condition and /‘/ denotes the complement of a variable). A ‘‘fault supervising network’’ is used in parallel, in order to monitor if a specific condition rmi is met within a specified time Ti, after the motor operation has started.

Thus, in addition to the external motor stop command emi, the situation of the ’’fault state’’ 6,mi is tested, via its associated boolean variable X6mi.

B. The valve module

Its operation is quite similar to the motor module. However, due to the simpler requirements of the valves, no fault supervising network is necessary.

Three motors are used: two for pump1 and pump 2 and the third for the agitator. Thus three motor modules are concurrently executed, the index mi belonging in the set {m1,m2,mA}. Additionally, five valves are used: four for the inlet and feed valves for the two pipes and the last for the drain valve. Thus, five valve modules are concurrently executed, the index vi belonging in the set {vA1,vB1,vA2,vB2,vD}.

4.3.2. Links and Interlocks

The execution of the above eight modules is synchronized and linked via appropriate conditions at their corresponding Receptivities.

These conditions are listed in Table 2 and involve external system inputs, as well as conditions of the states of individual nets.

Ap	es’*lf’*X1vD	Enable filling condition
sm1	s1*ap*l1*lt1’	Start motor of pump1
em1	e1+ap+lt1	Stop motor of pump1
rm1	f1	Verify flow at line 1
T1	5sec	5 secs after pump 1 starts
sm2	s2*ap*l2*lt1*lt2’	Start motor of pump2
em2	e2+ap+lt2	Stop motor of pump2
rm2	f2	Verify flow at line 2
T2	5sec	5 secs after pump 2 starts
svA1= svB1	X2m1*(t/2,m1/1sec)	Open valves A1,B1 1 sec after pump1
evA1= evB1	X1m1	Close valves A1,B1 when pump1 stops
svA2= svB2	X2m2*(t/2,m2/1sec)	Open valves A2,B2 1 sec after pump2
evA2= evB2	X1m2	Close valves A2,B2 when pump2 stops
aA	es’*lm*X1vD	Enable agitator condition
smA	sA*aA	Start agitator
emA	eA+aA	Stop agitator
rmA	cA	Evaluate if agitator speed is OK
T3	10sec	10 secs after its start
aD	es’*le*X1mA	Enable Drain Valve condition
svD	sD*aD	Open Drain valve
evD	eD+aD	Close Drain valve

Table 2: Automation system interlocks and links.

The overall system flow is as follows:

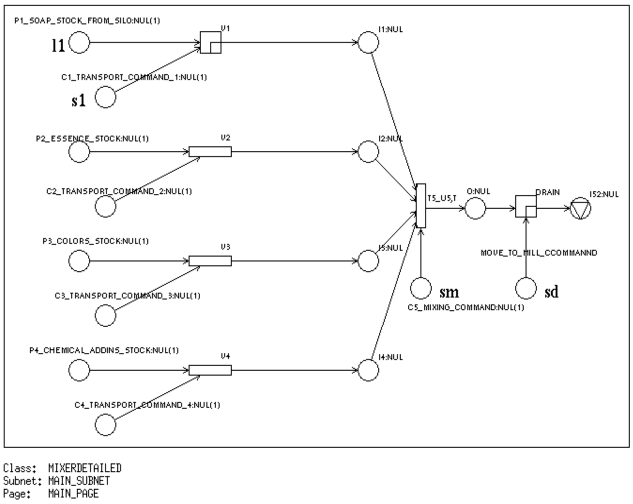
1) If material is present at the input of pipe 1 and the tank level is below a certain Level 1, the start button of line 1 activates pump 1. This pump operates till a stop condition (Emergency or stop_Line_1) is met, or Level 1 is reached, or a fault condition is met (No flow indication, 5 seconds after the start of the pump).
2) One second after pump 1 has started, the open command for valves A1 and B1 is issued simultaneously. The valves close when pump 1 stops.
3) Ingredient 2 is filled in the same way as ingredient 1.
4) The agitator starts mixing the ingredients.
5) The drain valve is opened after the end of the mixing.

It should be mentioned that the drain valve cannot open while mixing takes place, and that no filling or mixing is allowed with the drain valve open.

4.4 The detailed physical model

The detailed physical model can be constructed by transforming the production system physical model into an interpreted P-net and ’’zooming’’ at specific transitions of it. This concept is shown in Figure 7 for the mixing module of the production system. Transition V1 of the original net (Figure 3) is now transformed into an interpreted P-net with 3 transitions and 2 places, shown with more details the filling process for line 1.

This network receives as conditions (Receptivities) the actions of the automation system and produces certain physical outputs (Actions), that are used in turn as conditions in the automation model. A similar enlarged version is shown for transition DRAIN.



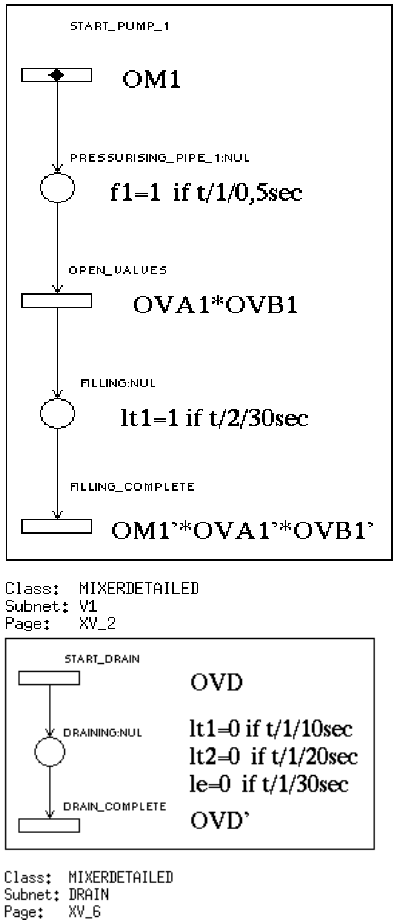


Figure 7. Detailed physical model.

Thus, the automation and the physical model can be executed simultaneously, enabling the simulation of the full system, with any necessary degree of details.

5. CONCLUSTIONS AND FURTHER RESEARCH

The utilization of the same tool (Petri-nets) for modeling the different components of the physical system facilitates largely the communication between the experts, reducing radicaly the design - installation time and increasing the flexibility and modularity of the system. It can lead to the simultaneous evaluation, both of the production plan, as well as the automation system, in conjunction with the detailed physical behavior of the system. Although this approach is currently shown off-line, it can be further shown, that the same integrated model can be used also for the real time supervision and fault identification of the system.

An interesting subject of research is to further extend this approach, in order to develop standard general purpose modules, including both the production system level, as well as the detailed automation and physical system model. Although the linking of these modules can be currently done via interpreted P-nets with Receptivities, Actions and Interlocks, some further research would be necessary, in order to bring the model in a form, more easily evaluated

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