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Petri Nets based automation of manufacturing systems

Training goals

The participants to this the training will

- Acquire operational skills on the use of Petri Nets tools for automation
- Be able to understand and apply methods for designing robust, deadlock free and performance oriented control solution for manufacturing systems

Unit 1

This unit will refresh the knowledge of the participants related to the following topics:

- manufacturing system
- modelling
- simulation
- automation
- flexible and automated manufacturing systems FMS/AMS

Manufacturing system [Basnet1994]

Modelling is the activity of model building. A *model* is an abstracted and simplified representation of a part of the reality, This mental construct allows the reasoning about the represented reality. In the context of this training a systemic view. Constructing a model consist in identifying the states, inputs and outputs that characterize it, and determining the relations that quantify the dependence of the states and outputs from the inputs. In order to handle complex systems, the hierarchical decomposition in a collection of interacting subsystems is also used.

Once the model is defined, ***simulation*** is the method used to determine the possible evolution of the modeled system starting from a given state. It consists in substituting the values for the starting states and inputs in the model relations and calculating the following states and corresponding outputs.

A ***manufacturing system*** is an ensemble of humans and machines that interact in order to transform raw materials in finite products.

Automation groups the techniques by which the human contribution to the command and control of a process is reduced or eliminated. The goal of the process control is to maintain the values of the process outputs in the close vicinity of a set of given values (reference values).

Automated manufacturing system (AMS) are manufacturing systems that can handle the manufacturing of a finite products with little or no human contribution. This include the transport of material from a workstation to other, the control of each workstation, the synchronization of workstations, the inspection of materials and redirection of nonconforming products.

Flexible manufacturing system (FMS) are manufacturing systems able to reconfigure themselves very rapidly in order to produce multiple types of products. A FMS consist of:

- a set of workstations capable each of executing automatically a larger set of operations so that *machine flexibility* is provided. This assures that the system can absorb large-scale changes in volume, capacity, or capability demands.
- an material handling system based on flexible conveyors, automated guided vehicles (AGV) and loading-unloading robots that facilitate the transfer of material and tools from one workstation to other. This must provide *routing flexibility* which is the system's ability to be changed to produce new product types, and to change the order of operations executed on a part.
- a complex command and control system that orchestrates the cooperation of the before mentioned systems

In the second part the Petri net modeling theory, language and graphical notation is presented. The tools used for model development, for the simulation of the models and for the formal, qualitative and quantitative analysis of the systems are also presented

Petri net theory was originally developed by Carl Adam Petri and presented in his his Ph.D [Petri1973]. The common definition of PNs introduced by Petri is as follows. A Petri net or place/transition net can be defined as a five-tuple;PN = (P, T, I, O, Mo) (1) Where:

- P and T are a finite non-empty sets of places pictured through circles and transitions pictured through rectangles, respectively. P and T are disjoint sets, and $P \cup T$ are called nodes with $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$
- I and O are input and output functions that defines the set of directed arcs from T to P. More obvious, the input and output functions of Petri net can be represented by arcs with arrows between two different types of nodes.
- $M: P \rightarrow N$, is a marking whose i^{th} component represents the number of tokens in the i^{th} place Pi.. The initial marking of the net is denoted by The Petri nets are assumed to be connected; it means that there is at least one path between any two nodes.

Figure 1 depicts a classical problem in concurrent system, the philosophe's dinner. Four philosophers take a common dinner at a round table. They eating rice with sticks. The problem is they have only 4 sticks. To eat each philosophe needs 2 sticks so he can do two things: eat if both the left and right sticks are available or think if not both sticks are available. Figure 2 presents the corresponding Petri net that models the system

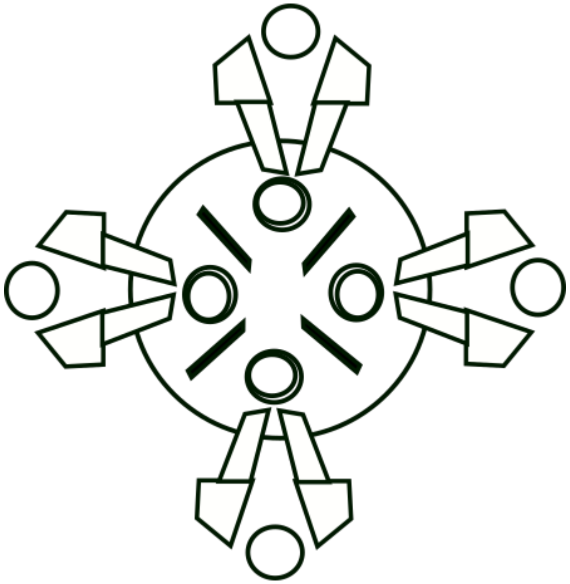


Figure 1 The philosophers taking dinner

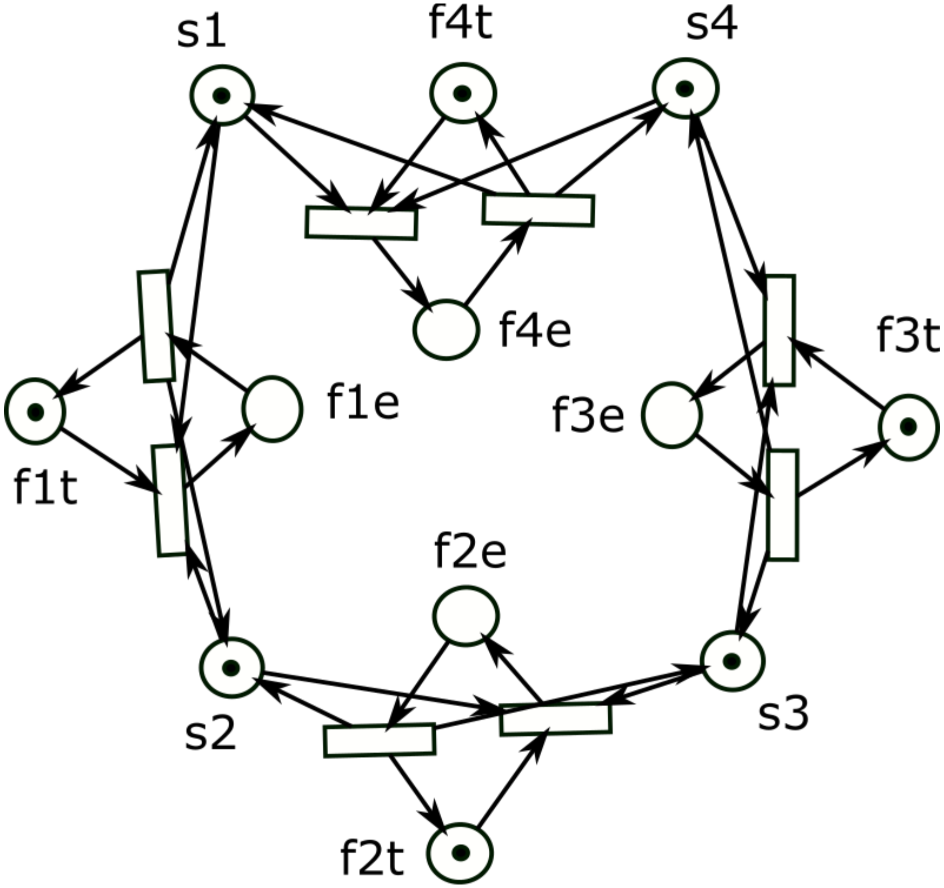


Figure 2 The Petri net modelling the philosopher’s dinner

Design classes

- Stage 1 The students learn to model the plants and the automation system using the Petri net using a mix of think-pair-share and problem solving

Unit 2 Modeling and simulation of manufacturing systems using Petri net

In representing a manufacturing system through a Petri net [Kaid2015], the initial marking Mo represents the different raw parts that are to be synchronously processed in the system and the state of resources, such as machines and robots. A marked PN and its elements are shown in Figure 1. In generally, places are used to represent the resource status, operations, and conditions, the transitions are used to express the control evolutions from one state to another, processes, activities, and events, directed arcs correspond to flow the material, resource, information, and control flow direction between states, while tokens are used to represent the material, information, and resource. Note that in a Petri net model the transitions may be immediate or timed, and in conflict or concurrent. When a token is located in a place, the place is said to be "enabled". When a token flows from one place to another, the process is referred to as "firing". Immediate transitions fire as soon as they are enabled. In timed transitions or places, there is a delay between enabling and firing. A timed transition is used to represent the start and end of system activities. A timed transition may be deterministic time or exponential, fuzzy, uniform, or any discrete and continuous probability distributions. The behaviour of the system is described in terms of the system states and their changes. In a PN model, the system state is defined by the marking marking. The new system state appears when the transition fires.

The flexible manufacturing system (FMS) represented in figure 3 is similar to the philosopher/s dinner. 4 robots are working on 4 workstation They can work only in pairs so only when both the left and right robots are available the workstation is used. The system is modeled through the same Petri net represented in figure 2

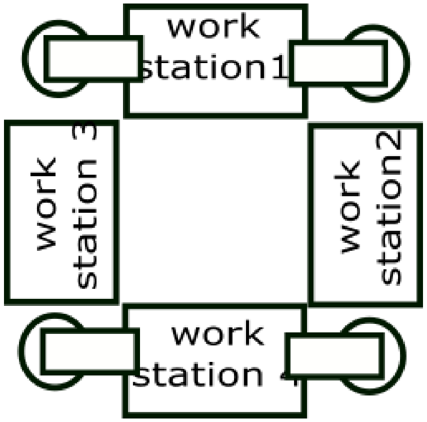


Figure 3 FMS equivalent to the philosophers dinner

Unit 3 The Automation System

Supervisory control is the process of limiting the action of a plant (described as an DES) to a set of safe, allowable or desirable behaviors.

The controller place is a place in the net that contains a token that can enable or disable some transition to attain a controller goal.

Controllable transitions are transitions representing events that can be influenced from outside. Arcs can be drawn from the control place to the controllable places. This corresponds to the actuator part of a control loop. Uncontrollable transition represent events that can't be influenced from outside. No arcs must exist from the control place to the uncontrollable places

Observable transitions represent events that can be observed or measured. Arcs can be drawn from the observable places to the control place. This corresponds to the sensor part of the control loop. Unobservable transition can't be observed or measured. No arc must exist between the observable places to the control place.

Standard procedure of control design based on incidence matrix and constraint formulation

The standard procedure use the incidence matrix for plant and supervisory control decomposition. They are two possibilities

1) That all transition are controllable and observable
2) Some transition are not observable/controllable

We will use in the design the following theoreme of controller synthesis described in [Moody98]

Let a plant Petri net with incidence matrix D_p be given with a set of uncontrollable transitions described by D_{uc} and a set of unobservable transitions described by D_{uo}. A set of linear constraints on the net marking, $L\mu_p \leq b$, are to be imposed.

Let $R_1 \in \mathbb{Z}^{n_c \times n}$ satisfying $R_1\mu_p \geq 0$ and $R_2 \in \mathbb{Z}^{n_c \times n_c}$ a diagonal matrix with $R_1 + R_2L \neq 0$ and let

$$[\,R_1 \quad R_2]\begin{bmatrix} D_{uc} & D_{uo} & -D_{uo} & \mu_{p_0} \\ LD_{uc} & LD_{uo} & LD_{uo} & L\mu_{p_0} - b - 1 \end{bmatrix} \leq [0 \quad 0 \quad 0 \quad -1]$$

Then the controller

$$D_c = -(R_1 + R_2L)D_p = -L'D_p$$

$$\mu_{c_0} = R_2(b+1) - 1 - (R_1 + R_2L)\mu_{p_0} = b' - L'\mu_{p_0}$$

exists and causes all subsequent markings of the closed loop system to satisfy the constraint $L\mu_p \leq b$ without attempting to inhibit uncontrollable transitions and without detecting unobservable transitions

Assignment 1

The system from figure 4. It comprises three stations: the actual working station where the work is done using tools that are wearing. When a tool is wearing over an specified limit it is transferred to the sharpening station by the transfer device trans2. After they are sharpened the tools are transferred to the reserve station by the transfer device trans3. From here they are transferred back to the work station.

Our model captures only the flow of tools. The particularity of the flow is that the weared tools ar evry time removed from the work station so this operation is considered uncontrollable.

The task is to design a control system that limits the number of tools that are concomitantly sharpened so that the capacity of the sharpening station is not overpassed

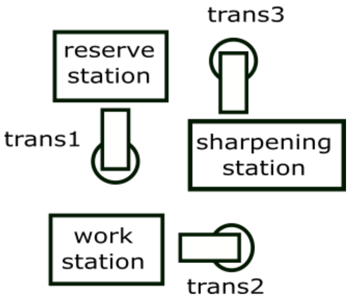
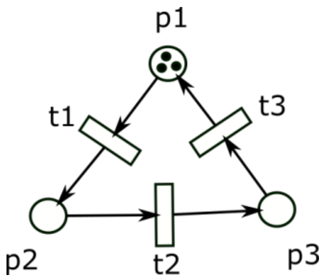


Figure 4 FMS with wear of tools

Solution

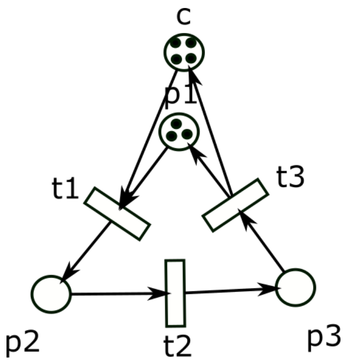
The Petri net (adapted from [Moody98]) corresponding to the system is presented in figure 5



The places correspond to the stations, the tools are represented trough token and the transitions represent transfers between the station. Corresponding t2 is unobservable.

The first step is to build the corresponding incidence matrices

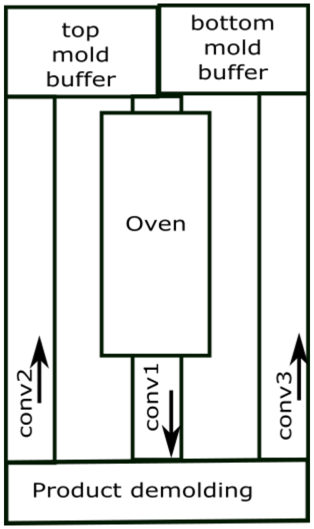
Figure 5 Petri net for the FMS of figure 4



The controlled system is represented in figure 6. As resulting from the Dc matrix, te control place observes t3 and controls t1 limiting the number of tokens in p3.

Figure 6 Plant- controller loop for system

Assignement 2

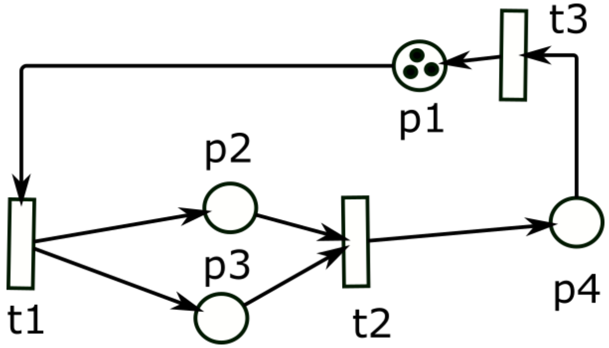


The second system, represented in figure 7, is a manufacturing system that produces molded products that are hardened through backing in oven. A two-part mold is used. The raw material(dough) is poured in the bottom mold - thaken from the bottom mold buffer- and covered with the top mold –taken from the top mold buffer. The two parts are assembled and the closed mold with the material is put on the conveyer belt 1 and transported through an oven where the content si hardened under the influence of high temperature. After exiting the tunnel, the product is demolded, the mold are parted again and the top and bottom part are transported separately on the conveyors belts 2 and 3 to the corresponding buffers. The loading of the oven is not controllable as every pair of molds parts available on the conveyor belts is assembled and introduces in the oven. The oven has a limited capacity.

Figure 7 Two part mould based manufacturing syystem

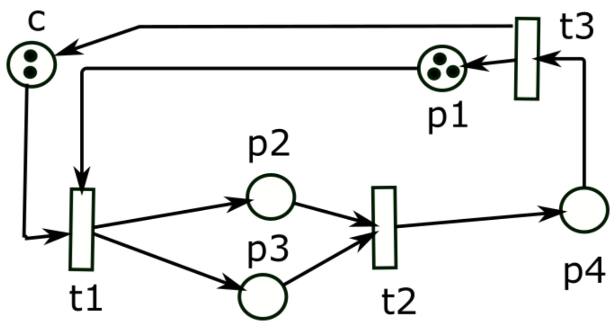
Solution

The corresponding Petri net (adapted from [Moody98]) is represented in figure 8



The product demolding is represented by transition t1, p2 and p3 represent the two mold buffer, t2 is the loading on the conv1 conveyor, t3 is the unloading from the conv1 conveyorm, p4 is the conv1 conveyor in the ovenm and p1 is the product buffer of demolding station. The transition t2 is uncontrollable. The initial marking is 3 in p1. The goal of the automation is to limit the number of tokens in p4

Figure 8 Petri net model of the system in figure 7



The controller corresponding to D_c is observing transition t3 and controlling transition 1. The net modelling the plant controller loop is presented in figure 9

Figure 9 Plant- controller loop for system

- Stage 2 The students learn to express the automated system specification as Petri Net properties that must be satisfied using a mix of case studies and problem solving

Unit 4 Deadlock control [Wu2012]

Most important studies in control using Petri nets are focused on deadlock control for manufacturing systems. A deadlock is a situation, which occurs when a process or thread enters a waiting state because a resource requested is being held by another waiting process, which in turn is waiting for another resource. If a process is unable to change its state indefinitely because the resources requested by it are being used by another waiting process, then the system is said to be in a deadlock.

Siphons are the most important feature of deadlock control

If all the minimal siphons have every time enough tokens, the system is deadlock free – it is live

Assuring that the siphons has every time enough token is controlling the system. A siphon can be:

- trap controlled – the siphon contains an trap that captures the necessary tockens

- invariant controlled – the siphon contains an invariant that assures that is every time marked with a constant number of token

Assignment 1 Controlled siphons

For the net in figure 10 ([Moody98] pag 126) identify the minimal siphon, if they are controlled and the type of control

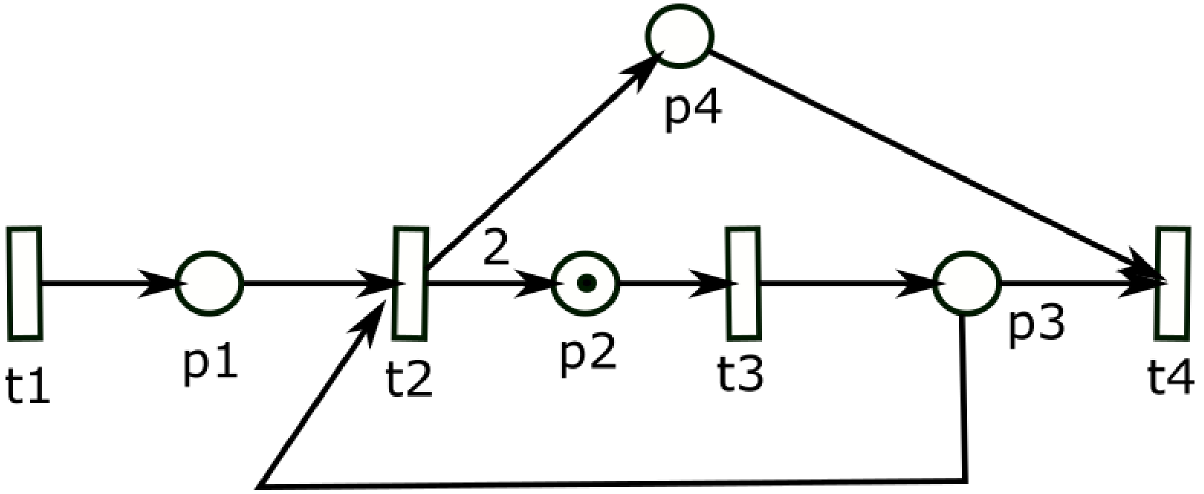


Figure 10 Petri net for a system with siphons

Solution

The net has two siphons S_1 p2.p3 and S_2 p2,p3,p4. The minimal siphon is S_1.

They are no trap and the only place invariant is m2+m3-m4=1

So m2+m3>=1.

So S2 the minimal siphon is invariant controlled and the net is live.

Deadlock avoidance through supervisory control

Assignement 2 Siphon controlling supervisors

Analyse the Petri net from figure 11 ([Moody98] pag 142) and design a supervisory control that should avoid deadlock

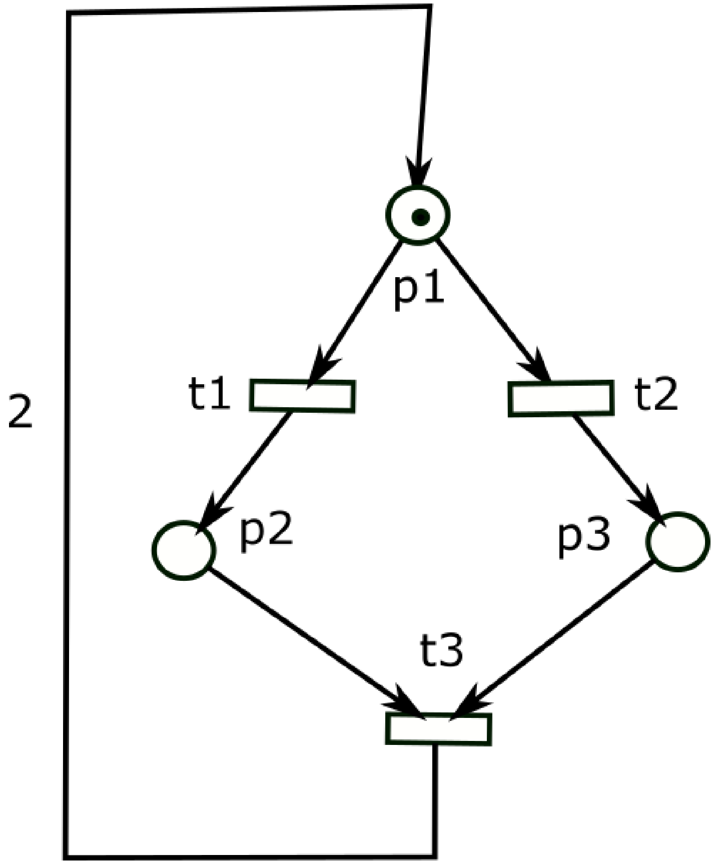


Figure 11 Free choice net with two branches

Solution

The net is a free choice net.

The net has three siphons S_1 p1,p2 S_2 p1,p3 S_3 p1,p2,p3. The net is well marked as p1 is part of all three siphons and is marked.

S3 is trap and invariant controlled but is not mininimal. S1 and S2 are minimal but not controlled.

So the controller places control the two minimal siphones S1 and S2. The net for the controlled net is presented in figure 12

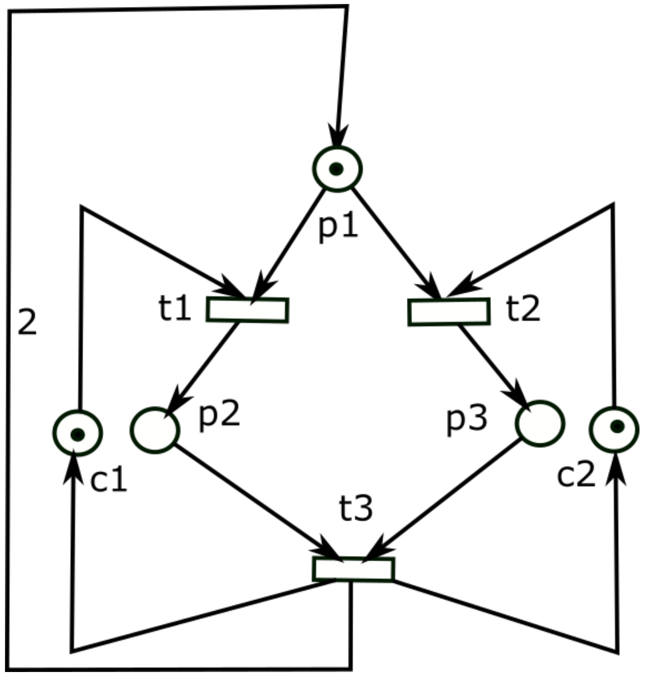


Figure 12 Controlled net

Assignment 3 Constraints on firing

For the network in figure 12 ([Moody98] pag 158), which is a possible model of the system from figure 4, implement the controller that limit the marking of place 2 to 1 token and inhibit the firing of t3 when the place is occupied

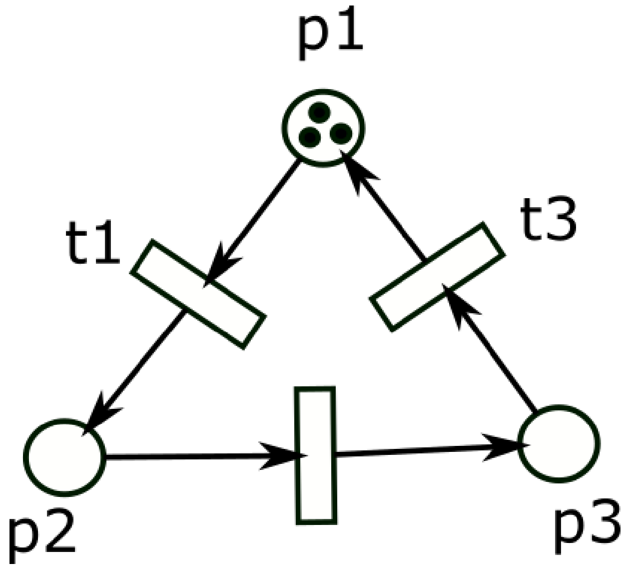
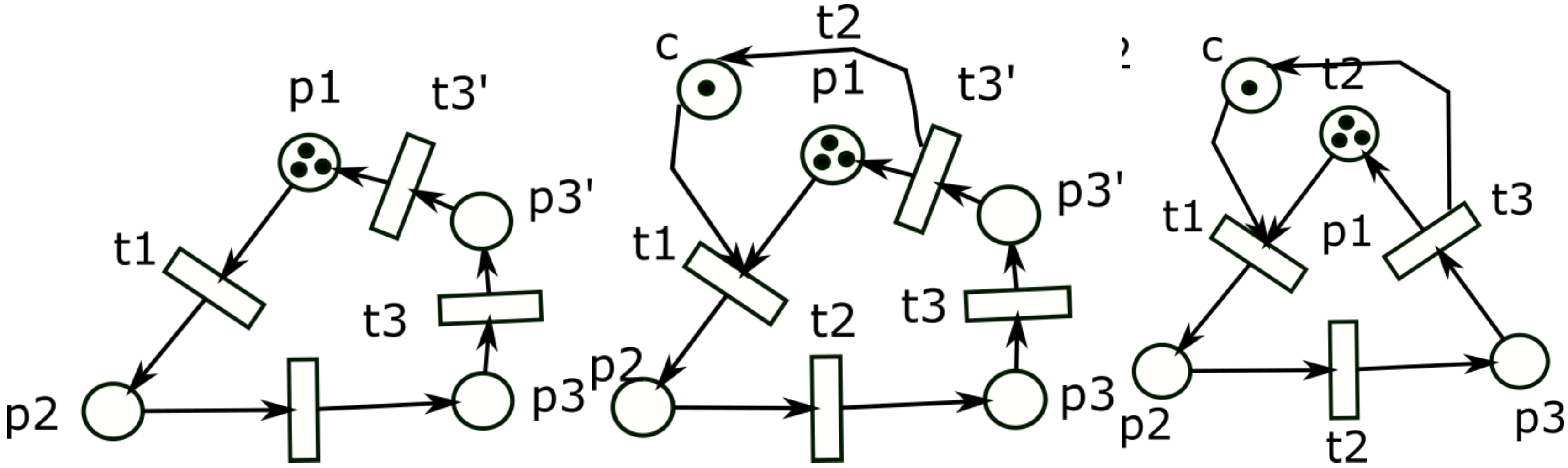


Figure 13 Petri net model for the constraints on firing

Solution

We introduce a supplementary place that separates the two constraints (a), implement the controller(b) eliminate the supplementary place (c)



a)

b)

c)

Figure 14 Steps of implementing the constraints on t3 firing

Assignement 4 Logical constraints

Implement a logical constraint that inhibits the firing of transition 3 when the place p1 contains a token in the net frpom figure 15 ([Moody98] pag 162)

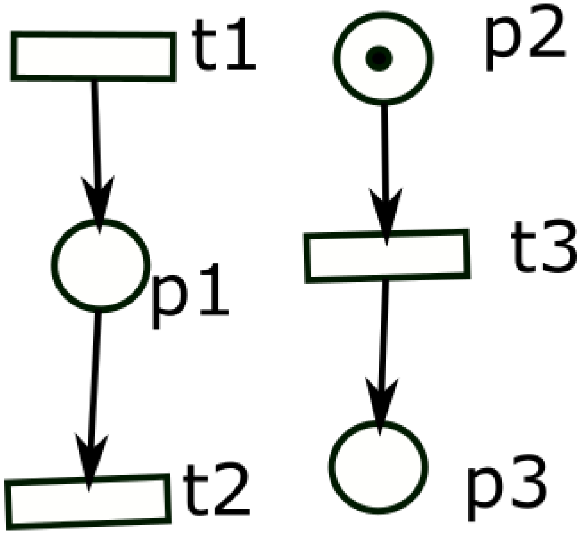


Figure 15 Exemple for the implementation of logical constraints

Solution

There are two possible solution :

- Introducing an inhibitpr arc wich ntroduce a new firing rules and reduces the generality of the Petri net and the number of applicable theorems (figure 16)
- Simulate the inhibitor arc through an construct (figure 17)

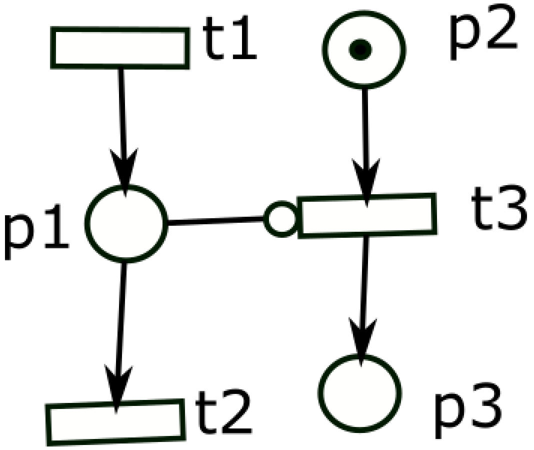


Figure 16 inhibitor arc

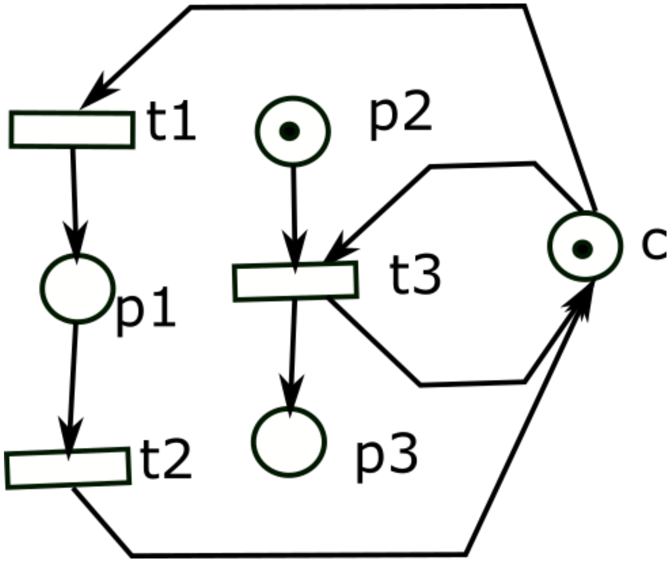


Figure 17 Structure equivalent to the inhibitor arc

Unit 5 Timed Petri Nets

Assignment 1 Not timed constraints

The system ([Moody98] pag 170) modeled through the Timed Petri net in figure 18 represents a processing plant wich has two branches on with the recirculation of parts and one without. Design the control net that enforces two constraints on the plan:

1. The capacity of place 2 should be limited at 3 tokens
2. The t5 transition should fire only when the p3 place is empty

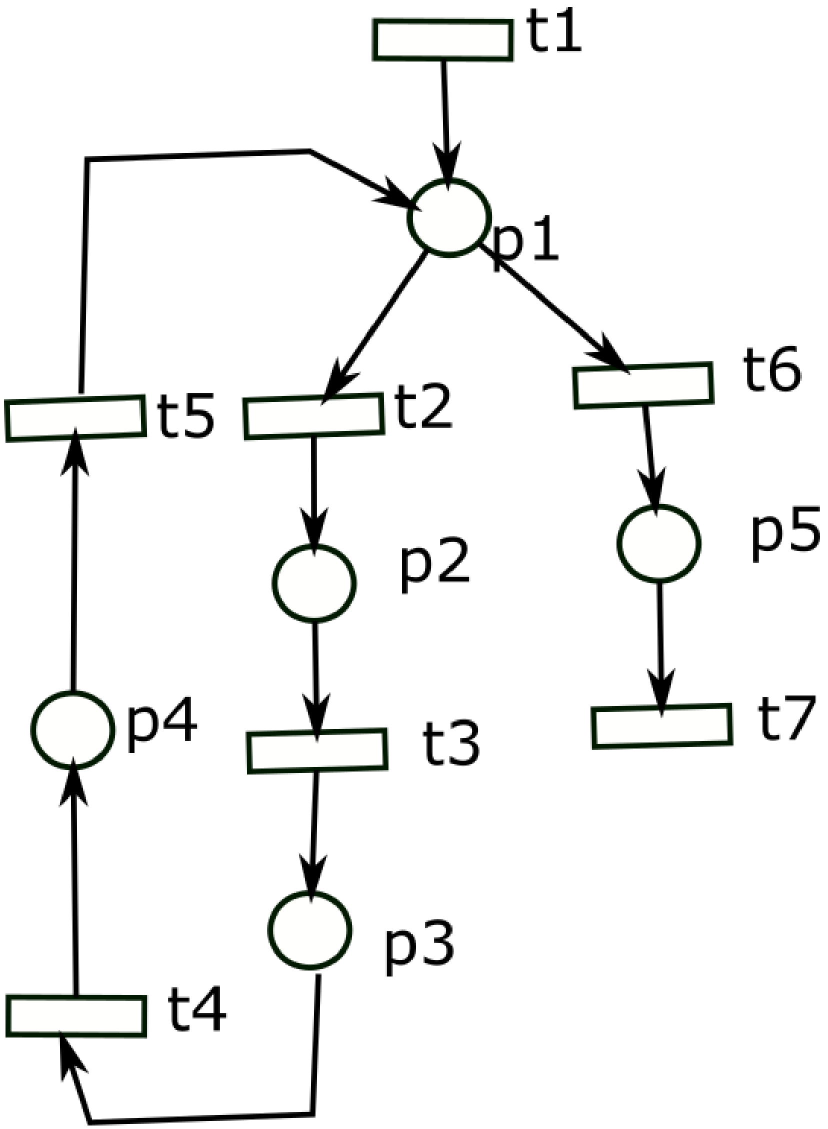


Figure 18 Timed Petri net

Solution

Whit the constraints expressed in the inequality form, using the standard controller synthesis procedure, the controller net forcing this constraints is implemented. The Petri net representing the controlled plant is presented in figure 19

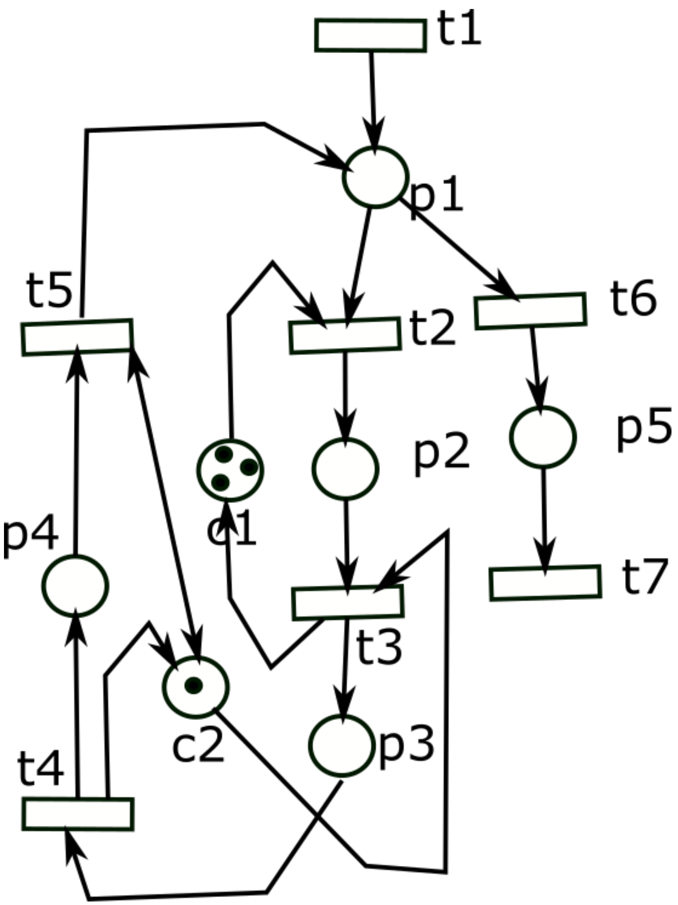


Figure 19 Controlled timed Petri net implementing untimed constraints

Assignement 2

Constraints involving time ([Moody98] pag 172)

On the structure in figure 18 implement a supplementary controller that should impose two timed constraint:

1) That t6 is not firing between 6:00 PM and 12:AM
2) That t7 can fire only after a time interval (e,g 2 minutes) has elapsed after the firing of t4

The rules will be impose a mixed constraint combining a marking and a firing event

Solution

To implement constraints that need the time of the day, a clock structure similar with that in figure 20 is used with the timing of the place p6 establishing the moment of triggering.

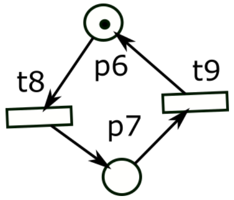


Figure 20 Clock structure

To implement constraints that implies lapsed period, a structure similar to that depicted in figure 21 is used.

The presence of token in p8 signals that from the last firing of t4 less than the time delay of p8 has passed.

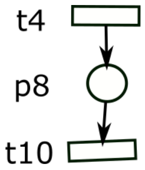


Figure 21 Timer structure

Taking in account this, the controlled net that satisfy the timed constraints is represented in figure 22

To assure that t7 is not firing if p8 contains a token (so that the temporizing effect of p8 is effective) but in the same time to not inhibit the transition t4 of firing the c4 with M token is introduced. M should be choosen in the range of expected number of firing for t4 or sufficiently large

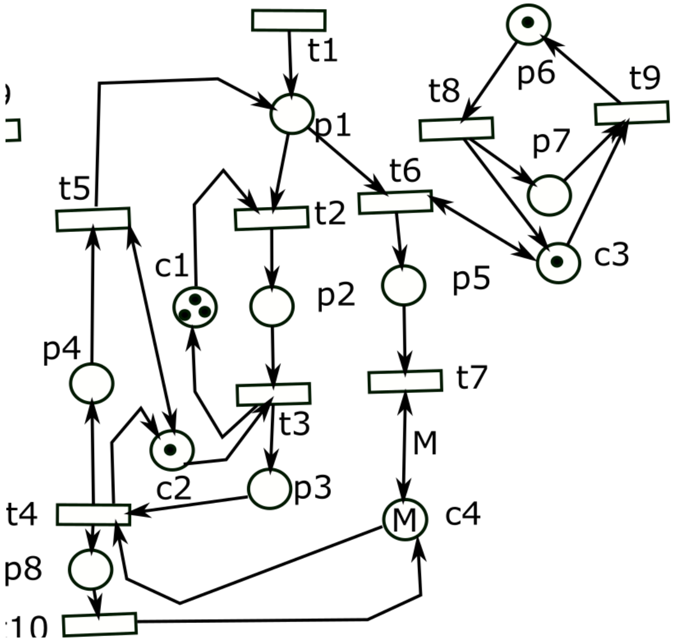


Figure 22 Controlled Petri net implementing Time constraints

Stage 3 The students learn to solve problems of supervisory control of an automared flexible manufacturing system

Unit 6 Supervisory control of FMS I

Assignement 1

For the plant described by the Petri net model in figure 23 (from [Moody98] pag 184)

- Design a control net so that that the two branches are taken alternativly
- Simulate the ansampb

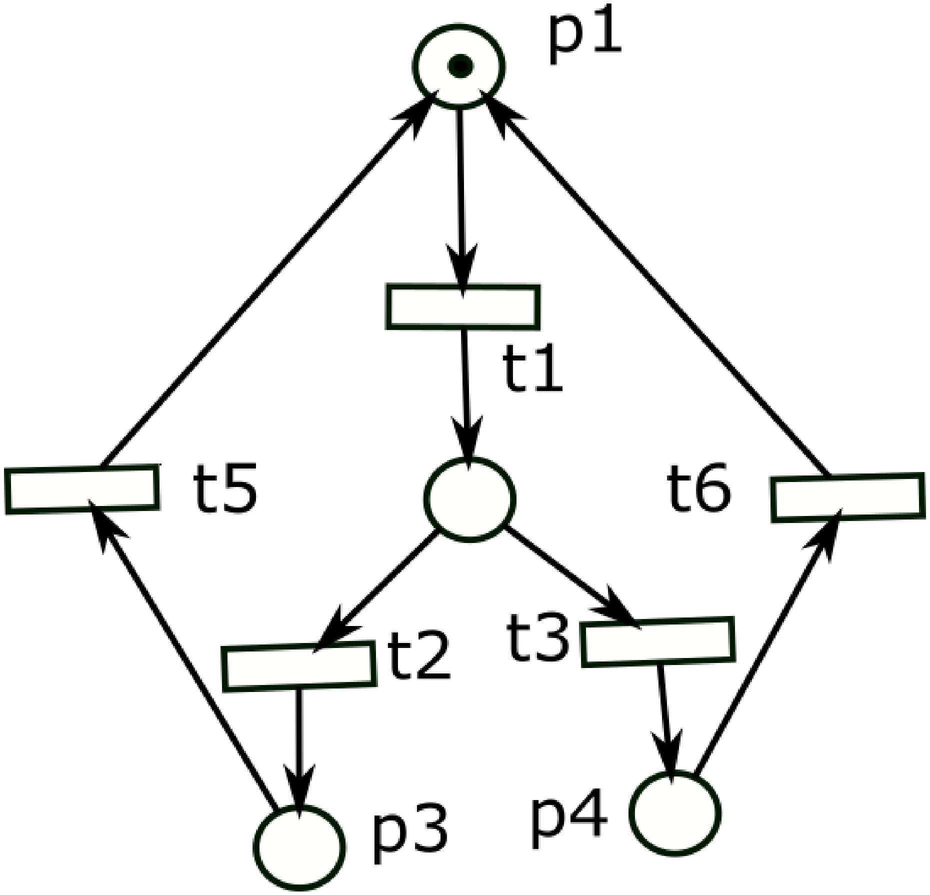


Figure 23 Plant model for the alternative path control

Solution

The ontroler synthesis is achived by writing the mutual exclusion rules for the two branches as constraints on the marking of the places, Using the theorem and integer linear programing methods to solve the resulting matriceal equation, the structure and the marking of the control Petri net is determined.

In figure the Petri net that model of the controlled plant is represented.

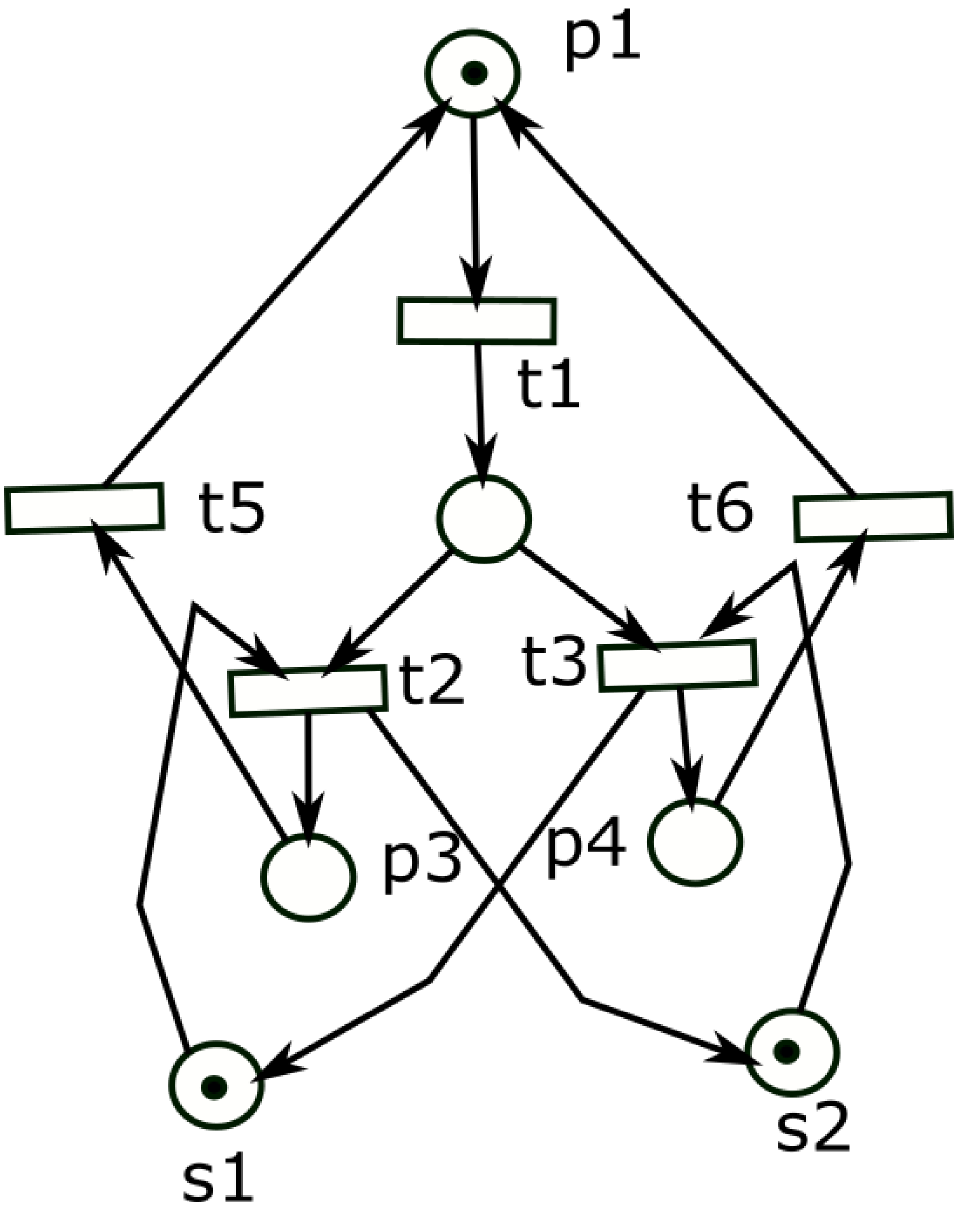


Figure 24 Controlled net with alternative path control

Assignement 2 For the plant described below::

Design a Petri net model that describes the modell

Design a control net so that that the

Simulate the ansampb

The plant represented in figure 25 is a flexible manufacturing system which uses Automated Guided Vechicles (AGV) to carry parts between the 3 workstations and the two buffers - one for the raw parts and one for the finite parts. There is one AGV which load a part from the output port of a source station station and unloaded it on the input port of the receiving station. Doing top the floor plan the trajectories of the AGVs are intersecting one each other. The control system should assure that no collision is tacking place.

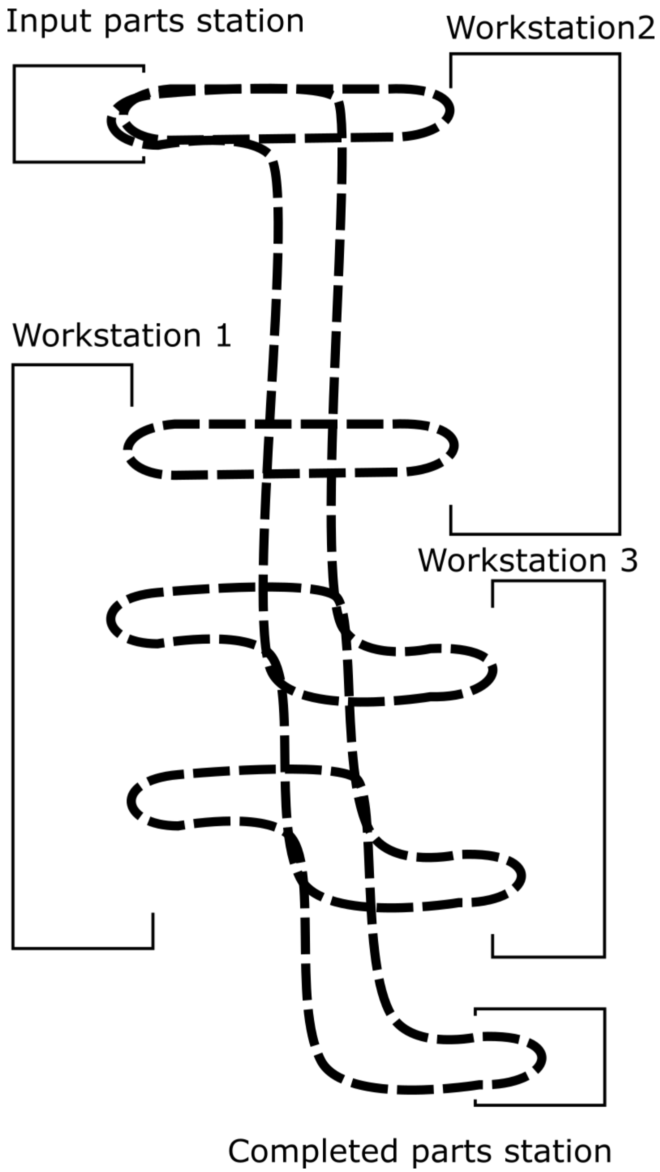
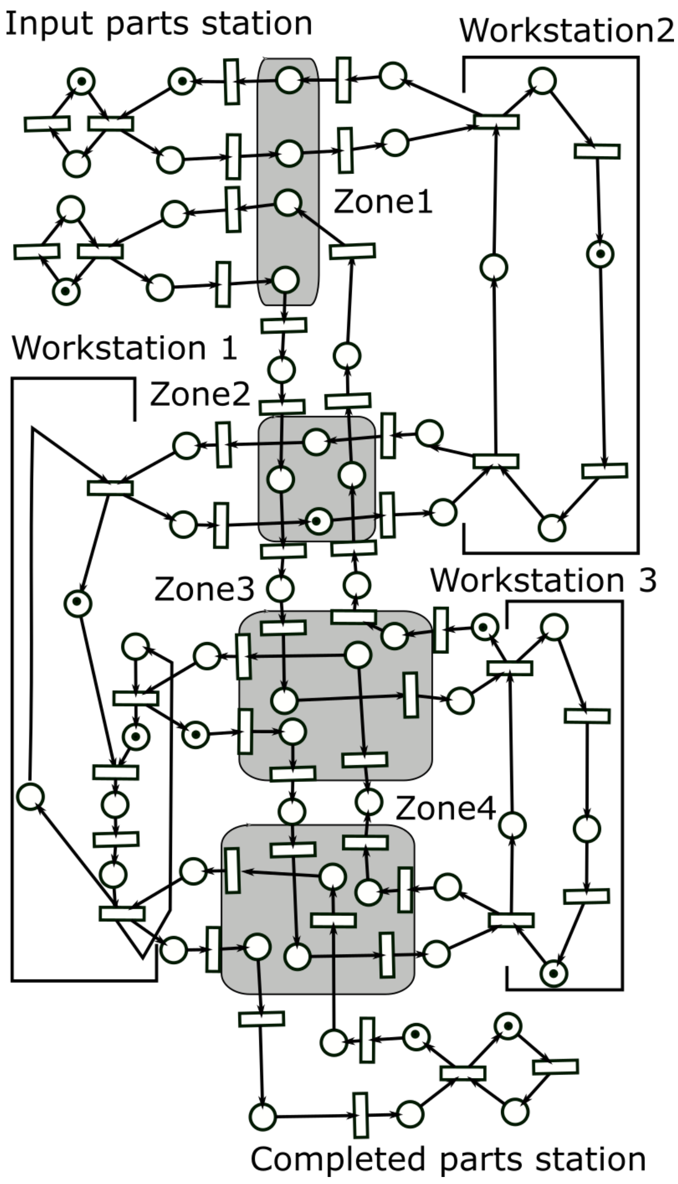


Figure 25 FMS with multiple intersecting AGV

Solution

Step 1 The Petri net in the figure 26 is a possible model of the plant. AGV is represented by a token. The trajectory of each AGV is constructed from the places that represent the important stations – in the workstation bays m in point where no collision can happen and points where collision can happen. So the control should assure that in the critical zones only oane vehicle is at oane moment



Each

Figure 26 Petri net model of the FMS with multiple intersecting AGV

Step2

After writing the avoidance rules as constraints on the marking of the places in the critical zones and using the theorem and the integer linear programing methods to solve the resulting matriceal equation, the structure and the marking of the control Petri net is determined.

In figure 27, the Petri net that model the controlled plant is represented.

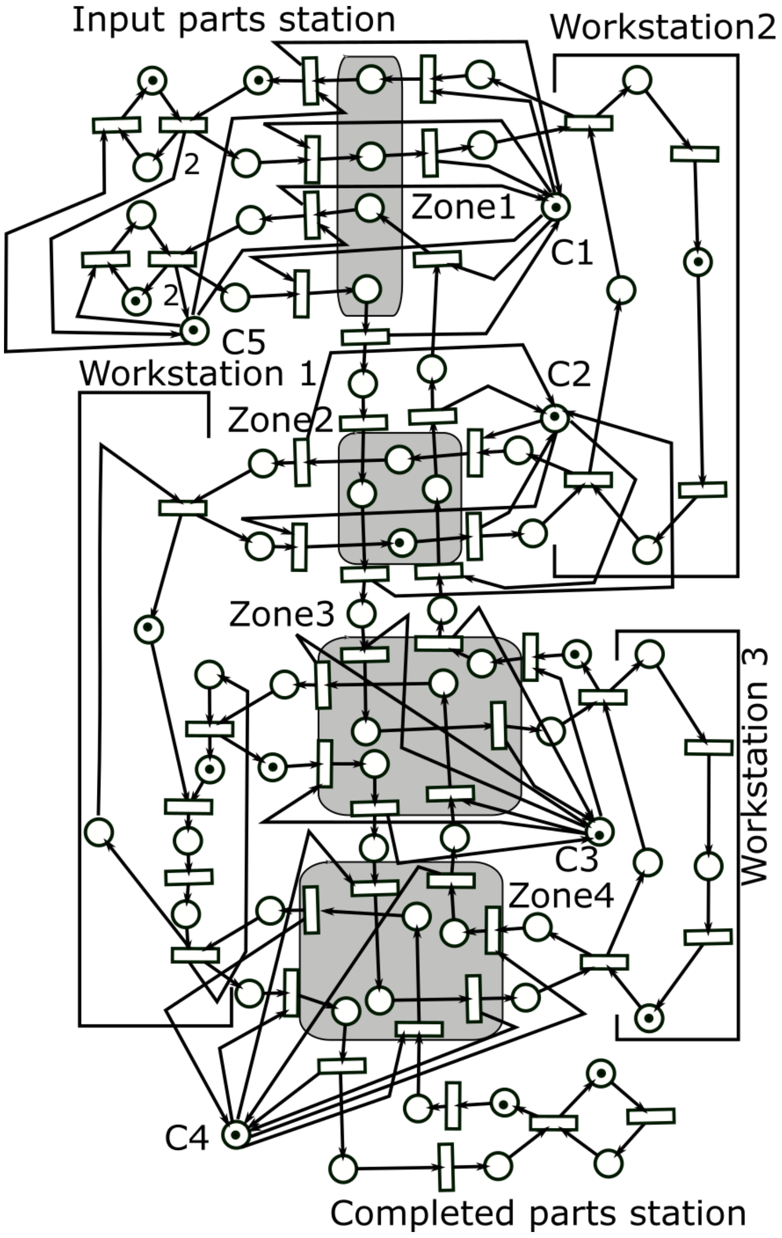


Figure 27 Petri net model of the controlled FMS with multiple intersecting AGV

Unit 7

Assignment 1

For the plant described below:

- Design a Petri net model that describes the model
- Design a control net so that that the
- Simulate the controlled plant

The plant (from [Moody98] pag 200) is presented in figure . . It consists of an unreliable machine which loads input parts from a conveyer belt and tries to transform them in finite parts. As a result of malfunction of the machine some of the parts are defective. Both the defective and final parts are transported to the corresponding buffer through an AGV

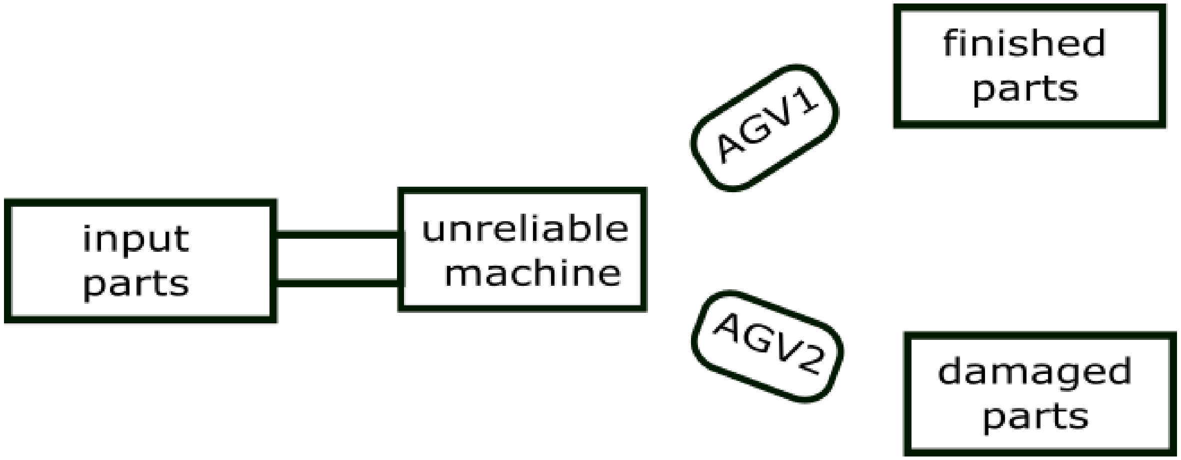


Figure 28 FMS with a unreliable machine

Solution

Steo 1

The following Petri net (figure 29) is a possible model for the plant

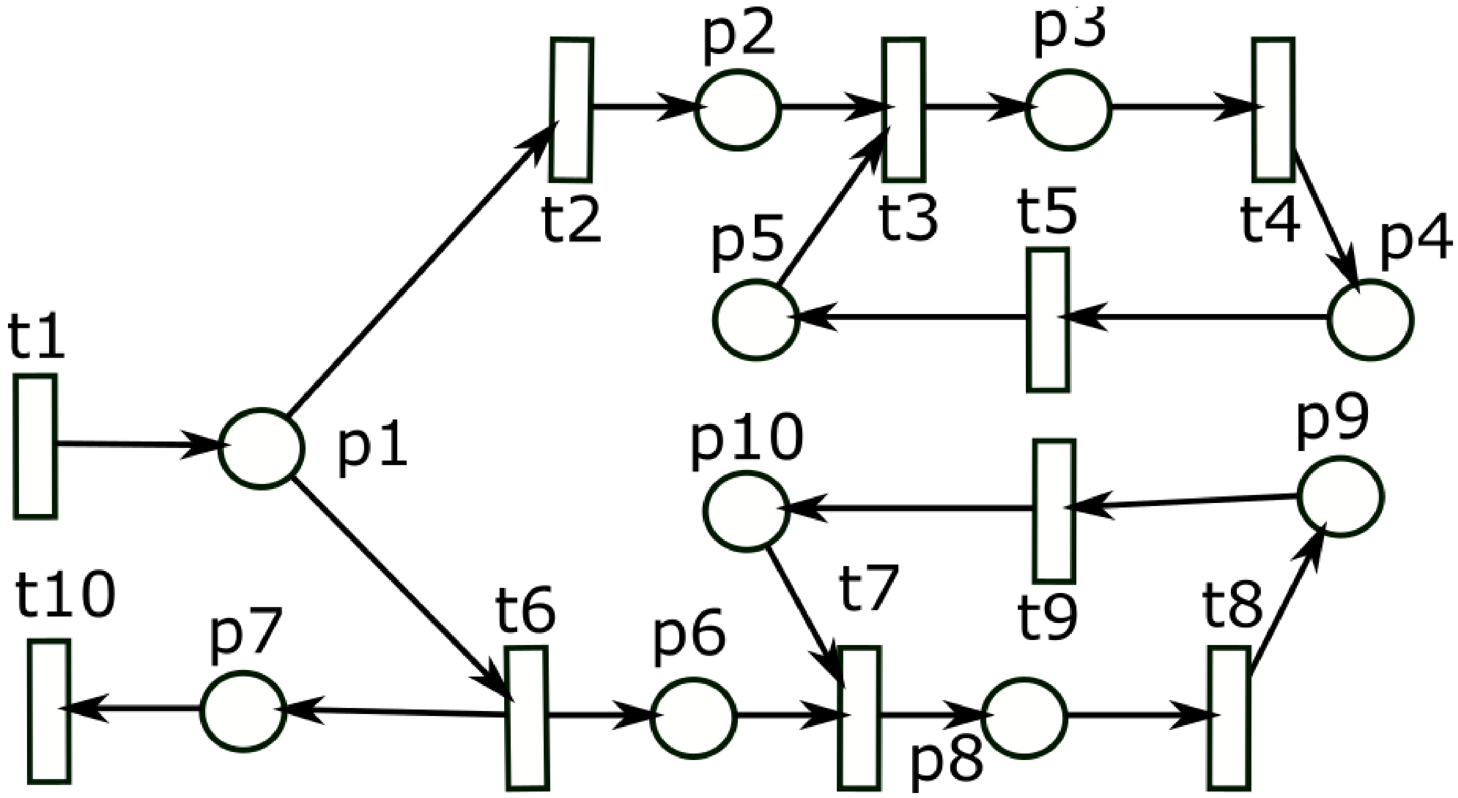


Figure 29 Petri net of the FMS with a unreliable machine

Step 2

Using the discriminant methode and the imposed constraints the control net is designed. The coupled plant controller net is similar with that of figure 30.

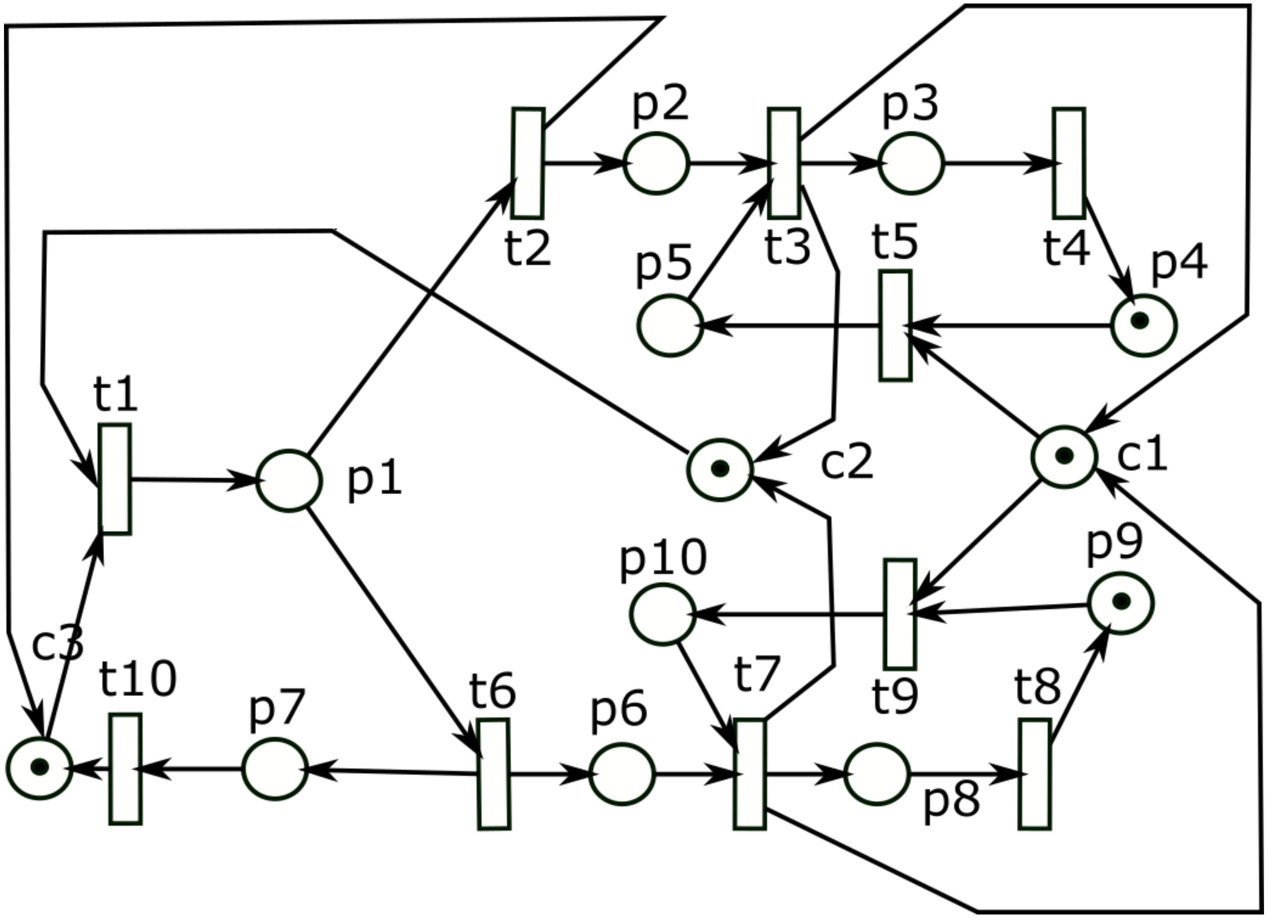


Figure 30 Petri net of the controlled FMS with a unreliable machine

Step 3

The designed net is maintaining the constraints but it must be investigated for deadlocks. The existing siphons ar not control so suplimentary control places are necessary for assuring the liveliness of the net. The resulting live net is presented in figure 31

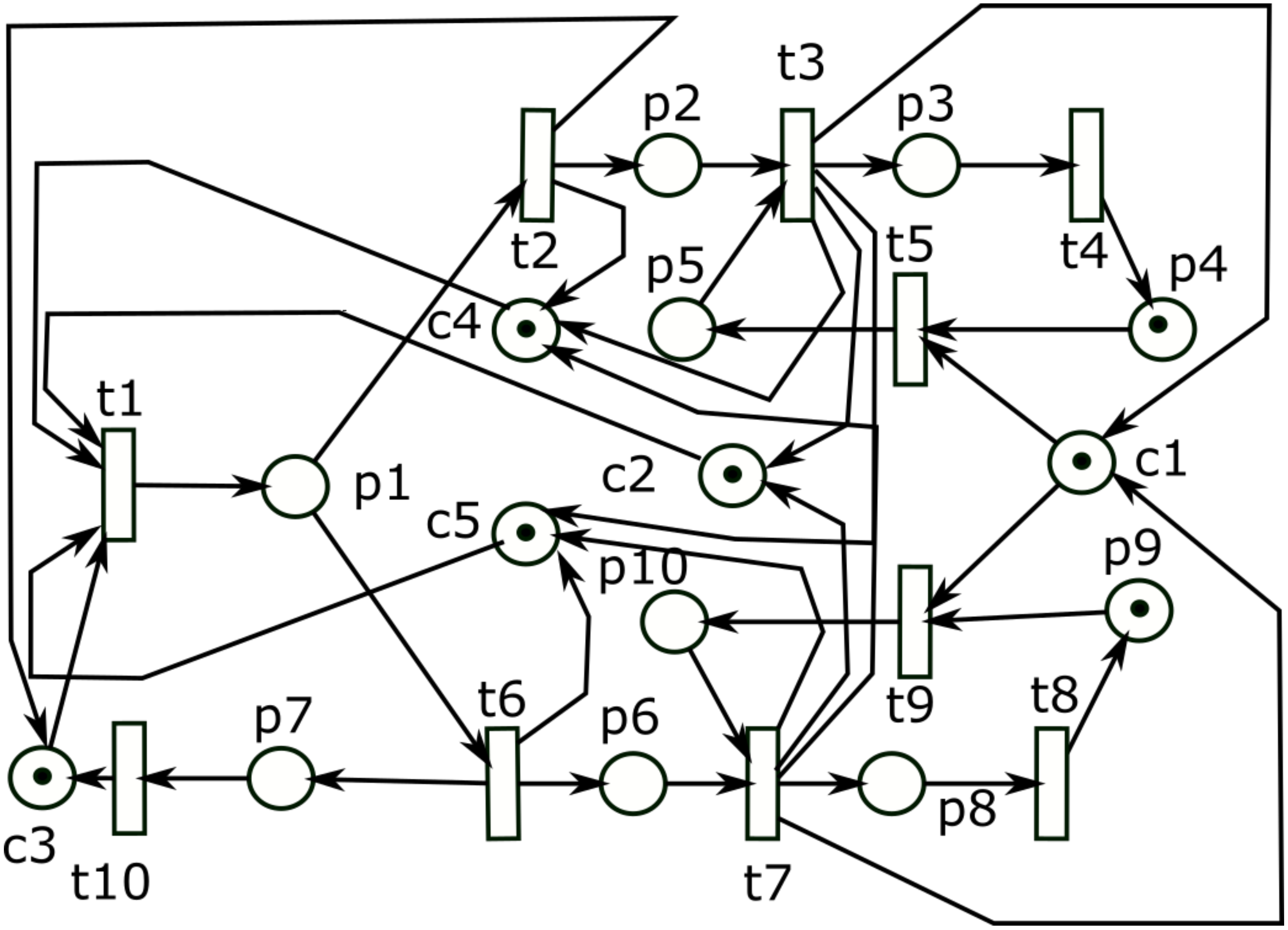


Figure 31 Model of the live controlled unreliable machine plant

Assignment 2

For the plant described below:

- Design a Petri net model that describes the model
- Design a control net so that that the
- Simulate the controlled plant

The plant (figure 32 adapted from [Moody98] pag. 227) consists of three tanks that can be filled with a liquid using a single pump. The tanks can be connected to the pump by opening one of the valves u_i . The operating of the valves is mutual exclusive so that only one at the time can be in use. The bottom part of the tanks is open so that the liquid is flowing free. Each tank has a maxim (h) and a minim level (l).

The goal is to conceive a control system that assures that no tank is overflow or underflow (i.e the level is kept between the high and low level in each tank).

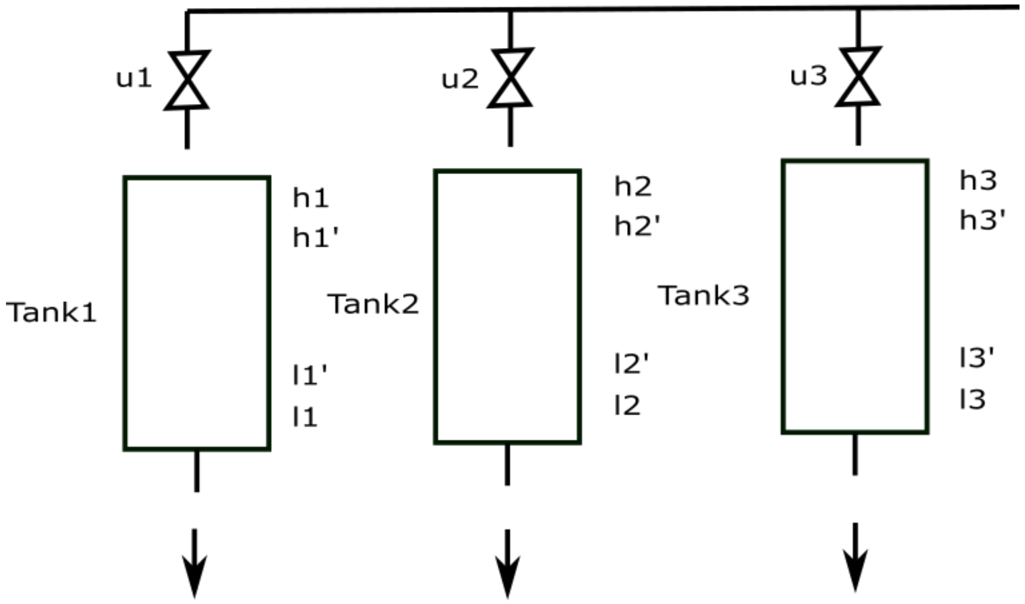


Figure 32 Three tank one pump system

Solution

Step I

Designing the Petri net model of the plant.

By considering the 5 stages – overflow, pseudo overflow (alarm level high), normal, pseudo underflow (alarm level low), underflow – three independent nets one for each tank can be drawn. A possible model is presented in figure 33. Each place represents one of the stages previous referred. The marking of a place by a token represents the tank reachimg this this stage. The transition are labeled with the corresponding commands that enable the transition. For example the tank 1 can pass from normal fill (p3) to pseudo overflow (p2) if u_1 is open and can go back if one of the other two valves (u_2,u_3) are open – and consequently u_1 is closed.

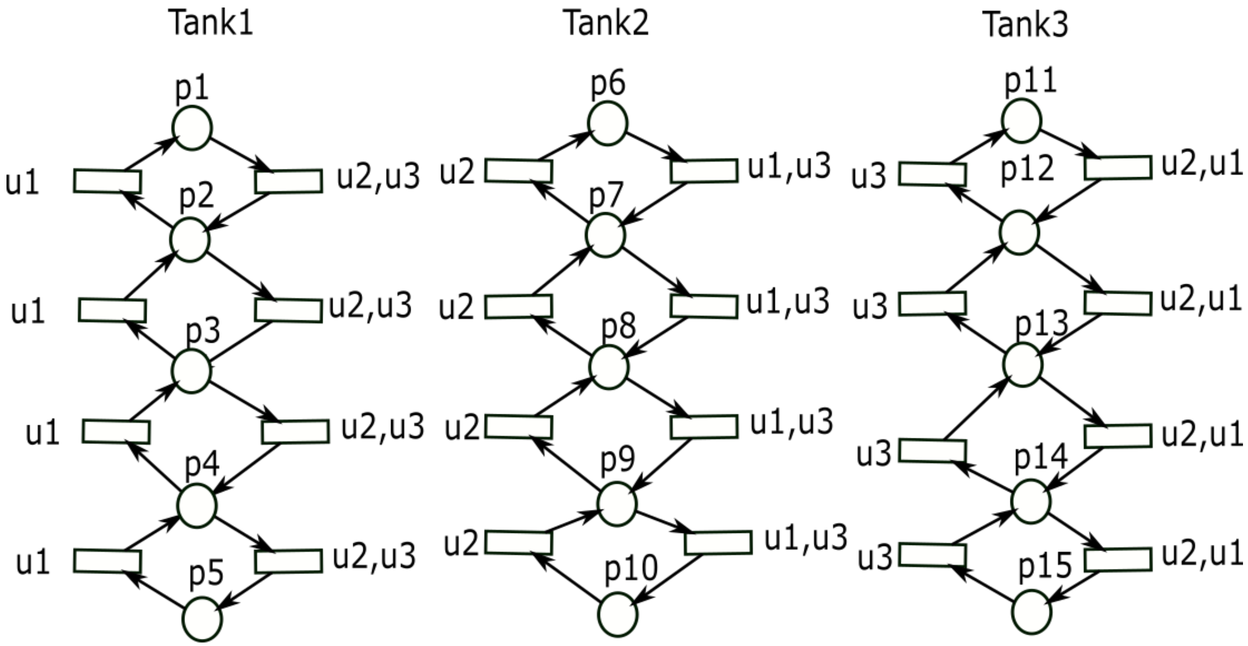


Figure 33 Petri net model of the three tank one pump system

Step2

Design the supervisory system. The controlled plant should not reach the forbidden states (under and overflow of each of thanks), So the plant model is reduced to the accessible places and the allowed transitions (figure 34). The controlled transitions are those corresponding to the opening of the valves t1,t2 and t3. The correspondence between the other places and transtions and the real event is given in the table 1

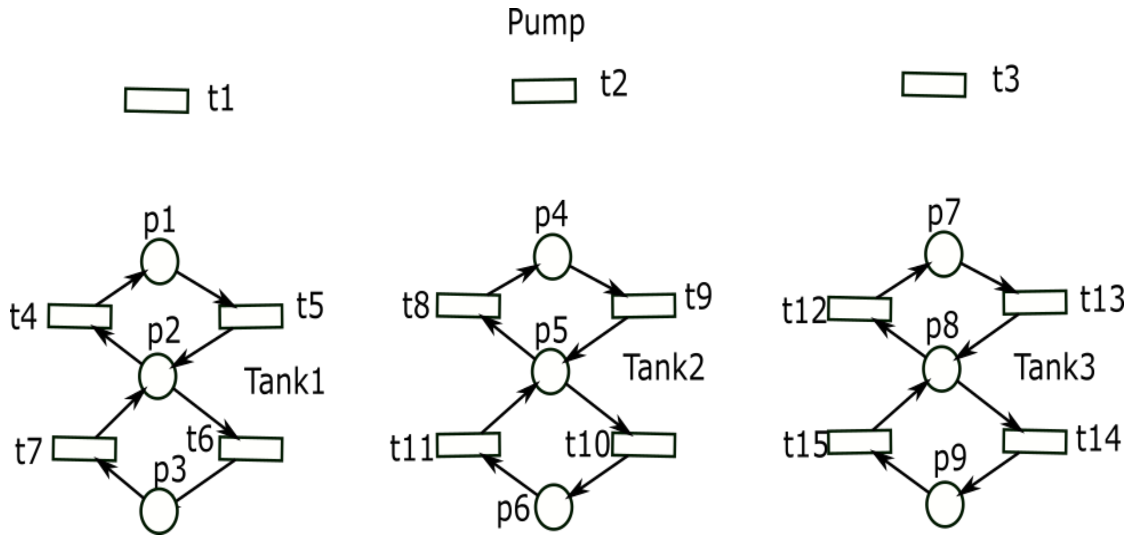


Figure 34 Reduced plant modell

Transitions	
t4,t8,t12	Pseudoverflow occurred.
t5,t9,t13	Pseudounderflow cleared
t6, t10,t14	Pseudounderflow occurred.
t 7;t11;t15	Pseudounderflow cleared.
Places	
p1;p4;p7	Pseudooverflow.
p2;p5;p8	Fluid level OK.
p 3;p6;p9	Pseudounderflow.

Table 1 Significance of places and transitions

Step 3

The constraints that the system must obey are defined. The control system should assure that the pump is coupled as soon as a tank to the tank has signaled pseudooverflow and decoupled from the tank that has signaled pseudoverflow. By formulating this condition as a mixt marking and event condition and by using the theorem to determine the conexions (D_c) and marking () of the control net a coupled control plant sismiar to the one in figure 35 is obtained

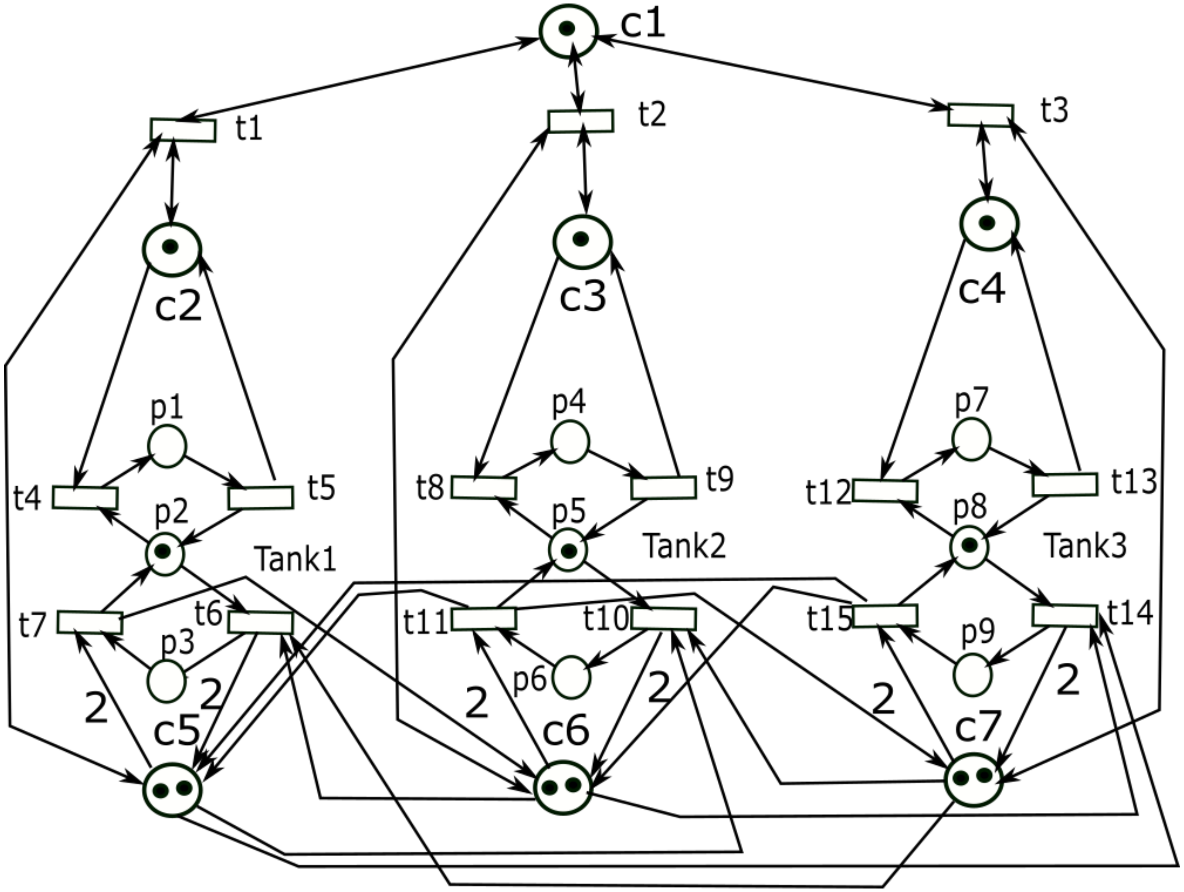


Figure 35 Model of the controlled plant for the three reservoir

Unit 8 Final assessment

The students will receive the task of solving in group a similar task to the complex task presented as example without receiving guiding. The functioning of the system should be proved by simulation.

References

[Basnet1994] CHUDA BASNET & JOE H. MIZE (1994) Scheduling and control of flexible manufacturing systems: a critical review, International Journal of Computer Integrated Manufacturing, 7:6, 340-355,

[Kaid2015] Kaid, Husam & A.M., El-Tamimi & Abouel Nasr, Emad & Al-Ahmari, Abdulrahman. (2015). Applications of Petri net based models in manufacturing systems: A review.

[Moddy98] Moddy, J (1998) Petri Net supervisors for discret events systems, Doctoral Thesis, Notre Dame University , Indiana , 1998

[Petri73] C. A. Petri*, Concepts of Net Theory*. MFCS 1973*: 137-146*

[Wu2012] Z. Li, N. Wu and M. Zhou, "Deadlock Control of Automated Manufacturing Systems Based on Petri Nets—A Literature Review," in *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 42, no. 4, pp. 437-462, July 2012.