MODELING OF ELECTRO-HYDRAULIC SYSTEMS USING CHANNEL - AGENCY PETRI NETS

Karol Muñoz Salas
Federal University of Santa Catarina – Mechanical Engineering Department - LASHIP – 88040-900 – Florianopolis – SC, Brazil
kmunoz@das.ufsc.br

Henri Carlo Belan
Federal Institute of Santa Catarina, IF-SC, 89.813-000, Chapecó - SC, Brazil
henri@ifsc.edu.br

Victor Juliano De Negri
Federal University of Santa Catarina – Mechanical Engineering Department - LASHIP – 88040-900– Florianopolis – SC, Brazil
victor.de.negri@ufsc.br

Abstract. *The present paper discusses a procedure to obtain models of hydraulic circuits using Petri nets and its interpretations, such as Channel-Agency nets (C-A nets), the Production flow schema and the Mark flow graph methodology (PFS/MFG methodology). A hydraulic system has a mechatronic approach because it is composed of electrical and hydraulic circuits and programs implemented in industrial controllers. As a consequence, the design of hydraulic systems is a complex task and the establishment of methods during the phases of their development is very important. In this context, this paper discusses a procedure that considers the models of the circuit structure and each hydraulic component. These models are obtained by applying the formalization for C-A nets and the PFS/MFG methodology. As a result, a complete model is obtained by using ordinary Petri nets, also known as a place/transition net (P/T net). In addition, Model Checking technique is use to analyze if the discrete – state behavior of the hydraulic circuit is according to the expected one. Finally, a basic application example is shown to illustrate the main features of this procedure. Therefore, the presented procedure intends to contribute to the improvement of modeling of hydraulic circuits.*

Keywords: hydraulic system, channel-agency net, automatic system, petri net, model checking.

1. INTRODUCTION

The automation and control systems have been continuously growing in many industrial sectors. De Negri (1996) described an automatic system as a set of interconnected components, which their main function is to carry out one or more actions according to a predetermined logic and in response to the equipment state. Also, automatic systems manipulate energy, matter and information flow with an intent to cause changes in the external environment. Therefore, the automatic system concept is closely related to a hydraulic circuit, since this is part of systems composed by sensors, buttons, actuators and programs installed in industrial controllers. The sensors capture information of the equipment or the process and they send this information to the programmable logic controller. The buttons, in the same way, receive operator commands. After the controller processes the received information, activates the hydraulic actuators through valves and emits illuminated signs for the operator, if necessary. In this context the hydraulic systems have been widely used because of the advantages offered, such as high reliability, good positioning accuracy and low power / weight ratio. Also hydraulic systems are complex; this is one of the reasons of interest on establishing methods for their design and analysis.

According to Henke (1970), the design of hydraulic systems is an intuitive process therefore a complex task, because it does not have an established process and only depends on the designer´s experience, plus the knowledge of the basic tools of this field. Consequently, there is a high probability of making a mistake during the design process. In bigger and more complex hydraulic systems, the probability of making a mistake is increased. On the other hand, the analysis of a system implies the existence of a system to be analyzed with respect to its performance characteristics. The intuitive judgment for this task is minimal, but it requires being an exhaustive procedure which covers all possible behaviors of the system.

This paper discusses a modeling and analysis procedure of hydraulic circuits. The modeling procedure considers the models of both the circuit structure and of each hydraulic component. The global model of the circuit is obtained by using C-A nets and P/T nets and by applying a similar procedure to the PFS/MFG methodology. Model Checking process is use to analyze if the behavior of the hydraulic circuit is according to the expected one. Model Checking technique performs an exhaustive search in the system representation.

A case study is also shown to illustrate the modeling and analysis procedure. Finally the results and the conclusions are related.

2. FUNDAMENTAL CONCEPTS

2.1 Systems modeling

Models are used to describe systems and are the result of applying one or more perspectives on the systems. The several options for modeling automatic systems essentially follow structural, functional and behavioral perspectives. The junction of these three perspectives allows a complete description of systems and also information integration among the system and other project tools is facilitated. The functional perspective describes function of each component in a system and the relationship among them to achieve a global function. On the other hand, the structural perspective details the set of elements in a system and also the connections among these elements. Finally, the behavioral perspective represents the relationship between inputs, from the external environment, and the internal state of the system. Likewise, this perspective also describes the system influence in external environment.

2.1.1 Petri nets (P/T nets)

Petri nets, also known as place/transition nets, are graphical and mathematical models, which allow designers to develop modeling and analysis techniques for automatic systems.

The elements of ordinary Petri nets are *transitions*, which represent actions, *places*, which represent states of the system, *directed arcs* which describe the interdependence of places and transitions and *marks,* also called tokens which indicate the condition associated with the place is verified. An important advantage when using Petri nets is that a hierarchical dynamic and a structure representation is possible, depending on the necessity to obtain a more detailed model (Murata, 1989) (Reisig, 1992). An example of a P/T net representing a vending machine is shown in Fig. 1.

The PFS/MFG methodology, as well as C-A nets are interpreted extensions of Petri nets.
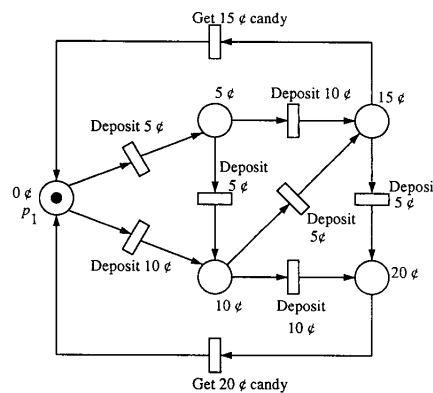

Figure 1. A P/T net representing the state diagram of a vending machine (Murata, 1989).

2.1.2 Production flow schema and Mark flow graph methodology (PFS/MFG methodology)

The production flow schema (PFS), as shown in Fig.2b, is a bipartite graph representation that is employed during the stage of conceptual design without considering a dynamic behavior. The importance of PFS is to identify active and passive components of the system and to represent the flow of items among its components (Miyagi, 1996). The elements of a PFS are: *activity*, which represents active components, *inter-activity*, which represents passive components and *arcs* which allow describing the logical relationship among the components of a system. PFS does not consider the use of marks.

Moreover, the mark flow graph (MFG) describes the dynamic behavior of the system and also considers external conditions which affect it, as shown in Fig. 2c. This methodology is also effective to specify and implement control strategies. The elements of a MFG are: *marks*, which indicate the maintenance of conditions, *boxes*, which represent conditions (preconditions or postconditions), *transitions*, which cause a state change of the system, *arcs*, which establish causal relationships between events and conditions, *gates*, which enable or inhibit transitions, and *output signal arcs,* which represents the interaction between the model and external elements (Gustin, 1999).

The PFS / MFG methodology is use to develop the dynamic behavior model of the system from a conceptual model. This methodology uses a top-down technique. It starts with a PFS model that is refined until a MFG model is obtained. Between the model in PFS and the model in MFG, there are many intermediate levels which facilitate system understanding. (Hasegawa et al., 1988).
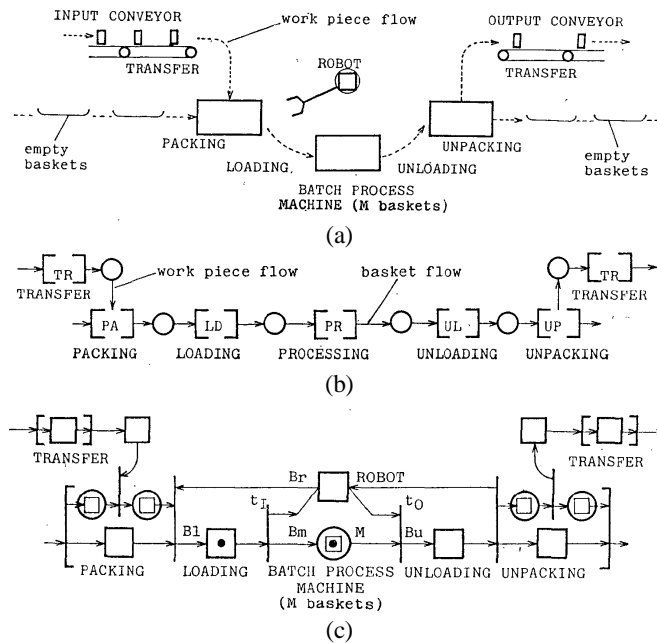
Figure 2. Example of a discrete event system modeled by PFS/MFG methodology. (a) System lay-out. (b) Production flow schema of the system. (c) Mark flow graph of the system. (Hasegawa et al., 1988)

2.1.3 Channel – Agency Nets (C-A Nets)

C-A net is a bipartite graph representation that is employed to obtain the functional and structural model of systems. The importance of using a C-A net is that it can be understood for any user because its elements are simple and easy to work with. The elements of a C-A net are: *active units*, which are represented by rectangles, *passive units*, which are represented by circles, and *arcs*, which connect active units and passive units representing the flow of resources. The passive units are the resources that flow through the system as energy, matter and information. On the other hand, active units represent operations that are applied on the resources. It is important to note the orientation of the arcs has no meaning under the structural perspective (De Negri, 1996). These elements are shown in Fig. 3.

According to Miyagi et al. (1999) and De Negri and Santos (2007), the C-A net and the PFS can be considered equivalent models. Both allow a conceptual modeling that uses a structural and functional perspective.

Figure 3. Elements of C-A nets. (Belan, 2007)

2.2 Systems verification

According to Cvijanovic (2011), simulation and testing are the most used verification techniques. Testing is performed on the physical product otherwise simulation is performed on the abstraction of the system. However, simulation and testing are not exhaustive procedures, because they cover only a limited set of possible behaviors. Consequently, they do not provide guarantees of safety and quality. This is the reason formal verification methods are necessary, such as the Model Checking.

Model Checking is a technique used for automatic verification of finite state systems. This technique performs an exhaustive search in the state-space system representation, in order to verify some properties. It is important to note that this method is able to detect the most subtle errors. As shown in Fig. 4., the technique begins modeling the designed system in an accepted representation by the tools of Model Checking. Also the properties that must be fulfilled by the system under consideration are described by using an accepted format such as logical formulas or automats. Finally, it is verified automatically if the properties were achieved using exhaustive exploration in the state-space representation of the system. If the properties are not verified, then the model of the system must be reviewed.
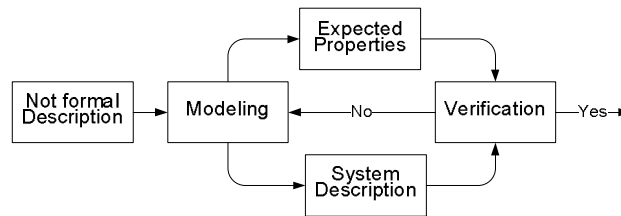

Figure 4. Model Checking (Farines, 2012).

As was explained, the expected properties of the system can be described using logical or behavioral approaches. These two approaches are complementary, since some properties can be expressed easily using logical approach and others properties using the behavioral approach. In the behavioral approach the expected properties are described by using P/T nets. Otherwise, in the logical approach the description of the desired properties is developed using logic formulas, also known as temporal logic.

The temporal logic uses propositions to make affirmations about states. These propositions are basic relations, which from a given state, have a true or false value. The logic operators AND ($\wedge$), OR ($\vee$), Negation ($\neg$) and Implication ($\Rightarrow$) can be used in these propositions. Also, the temporal logic uses temporal operators which allow describing propositions related to the sequence of the states during an execution. The temporal operators are: Next (*N*), Future (*F*) and Globally (*G*). (Clarke et al., 1999) (Diaz, 2010)

Properties, such as reachability, safety, liveness, fairness and deadlock can be represented using temporal logic. The Reachability helps to verify if a property can be achieved. The safety property describes a condition will never occur. The Liveness allows users to verify if under certain conditions something will happen eventually. Liveness is also stronger than reachability. The Fairness describes if something will not happen infinitely. Finally, deadlock expresses that a process cannot achieve a state from which it cannot evolve. There are other properties like the mutual exclusion, the response and the precedence, but these will always be described using the other properties. (Baier and Katoen, 2008)

Model Checking has many advantages over other verification methods. This technique is automatically performed and is quicker than other available methods. It is also important to note that the system model and the property, which designers want to verify, are the only things the user must provide. Furthermore, to start with the verification phase it is not necessary to provide the complete system model, the method can be use during the development of the model. Otherwise, the main disadvantage of Model Checking is the state explosion due to a very large number of states of the system model. All Model Checking tools have this problem and many researches aim to propose its solution (Clarke, 2008).

3. HYDRAULIC CIRCUITS PROJECT

The design of hydraulic circuits implies to synthesize an energy transfer system to perform a specific task. This is an intuitive process that requires the designer´s experience, plus the knowledge of the basic tools of this field, in order to find the best solution to a problem. (Henke, 1970)

The objective of this section is to demonstrate how little mistakes can generate an undesired behavior of systems during the design circuit, mainly considering hydraulic circuits design is a task that depends on the designer´s experience.

Fig. 5 shows a hydraulic circuit example. This example presents two circuits that have same components, but the connections between the directional valve and the actuator are different for each circuit. This difference between circuits results in displacement in opposite directions. In the case of Fig. 5a, when the directional valve is activated (parallel position) the cylinder moves forward. On the other hand, if the directional valve of the circuit of Fig. 5b is activated (parallel position), the cylinder moves backward as a result.
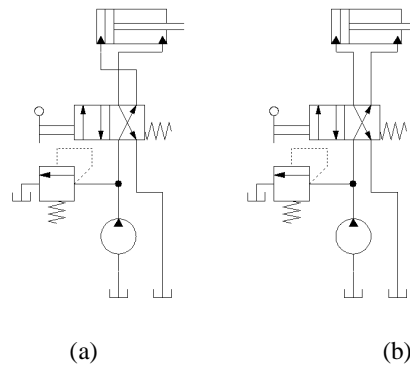
(a)   (b)

Figure 5. Circuits with the same components but with different connections between the valve and the cylinder.

A second example is shown in Figure 6. This example is from Linsingen (2008) that describes an elevation system with positioning obtained by a pilot operated check valve. According to Linsingen (2008), the elevator must maintain its position for a relatively long time, and its returning must be stable and controllable. If the directional valve is not activated (open center) the elevator holds its same position because of the effect produced by the pilot operated check valve. In these circumstances the only circuit pressurized comprehends the base chamber of the cylinder and the line connecting the port B of the check valve. Otherwise, when the directional valve is activated (cross position) to return the cylinder, it connects the pump line and rod chamber of the cylinder. The resistance to movement, imposed by the pilot operated check valve, increases the pressure in the pilot line (Port X) and consequently, allows the return of the cylinder. The graphic of the cylinder displacement of this circuit versus time is shown in Fig. 7 with was obtained by simulation AMESim®.
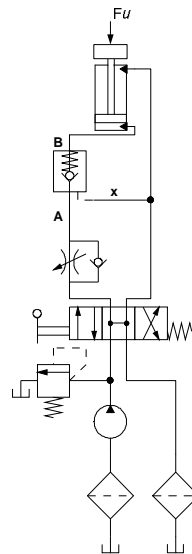

Figure 6. Elevation system with positioning obtained by pilot operated check valve. (Linsingen, 2008)
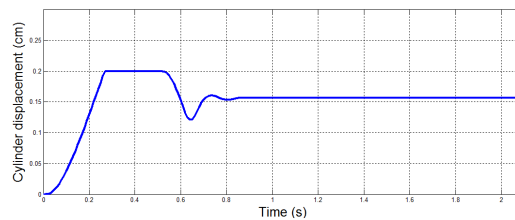

Figure 7. Cylinder displacements over time of the elevation system.

Figure 8 shows two variations of the hydraulic circuit for the elevation system. The difference of the circuit shown in Fig. 8a is it has a closed center valve. On the other hand, the circuit shown in Fig. 8b has also a closed center valve but it does not consider the use of a pilot operated check valve. The graphics of cylinder displacements vs. time of the two modified circuits were obtained by simulation AMESim® and are shown in Fig. 9a and Fig. 9b. According to the simulating results, these two circuits have a similar behavior. For this reason, when a closed center valve is used instead of an open center one, the pilot operated check valve does not accomplish its function of keeping the position of the cylinder. In the case of circuit shown in Fig. 8a, when the directional valve is disabled (closed center) the cylinder does not holds its same position because the pilot line (Port X) remain pressurized and the presence of valve leakage cause the return of the cylinder. It is important to mention that in sliding spool valves, as usual in directional valves, there is a clearance between the movable parts and, consequently, a leakage always exists.

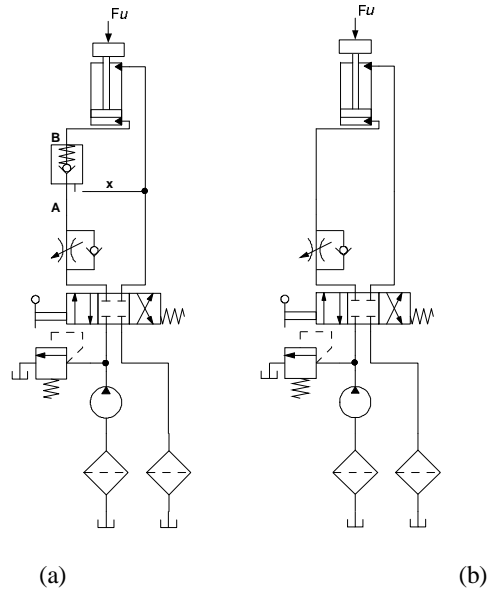(a)   (b)

Figure 8. Variations of the elevation system. (a) Circuit with a closed center valve. (b) Circuit with a closed center valve and without the pilot operated check valve.
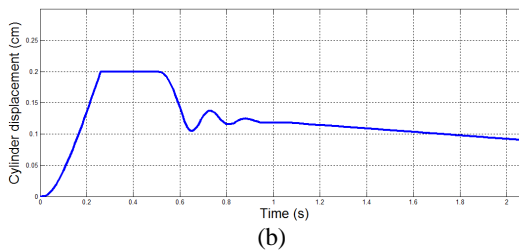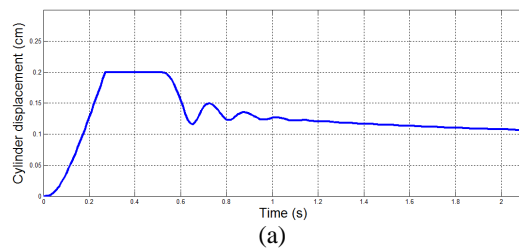

(a)

(b)

Figure 9. Cylinder displacements over time. (a) Circuit with a closed center valve. (b) Circuit with a closed center valve and without the pilot operated check valve.

The above examples show the design of hydraulic circuits is a complex task even in simple circuits, because it does not have an established process and only depends on the designer´s experience and knowledge. Consequently, there is a high probability of making a mistake during the design process. In bigger and more complex hydraulic circuits, the probability of making a mistake is increased. In consequence, it is important to develop methods of modeling and analysis helping to identify if the system is able to achieve its global function.

4. MODELING AND ANALYSIS OF HYDRAULIC CIRCUITS

This paper discusses a modeling and analysis procedure of hydraulic circuits using concepts of Petri nets and Model Checking. The procedure has four main blocks, illustrated in Fig. 10, and detailed as follows:
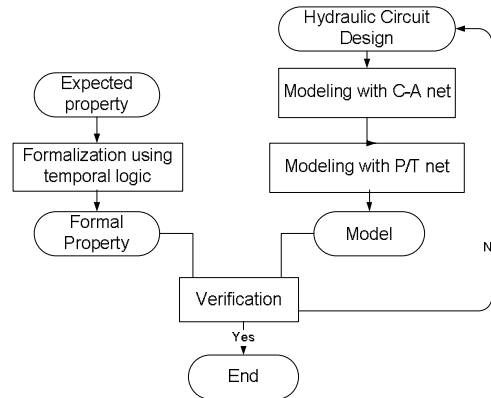

Figure 10. Modeling and analysis procedure of hydraulic circuits.

Stage 1: Modeling with C-A net.

This stage has as an input, the hydraulic circuit to be modeled. The components of the hydraulic circuit and the relationships among them are identified. The C-A net approach (De Negri, 1996) is use to build the model of the circuit which helps to identify the passive and active units of the circuit. This procedure uses C-A nets instead of PFS models because it already exists a formalism for C-A net (Belan, 2007) that allows to treat hydraulic systems mathematically. This situation could be advantageous if in the future certain conditions may require working with a mathematical formalization of the system.

It is important to underline that, C-A net is similar to PFS model because both allow the user to recognize the activities in a flow of discrete items and also these two model types have no dynamic. (De Negri and Santos, 2007) (Miyagi et al., 1999)

Stage 2: Modeling with P/T net.

This stage applies a similar procedure to the PFS/MFG methodology (Miyagi, 1996). In the PFS/MFG methodology is used a top-down technique. The PFS model is refined until a MFG model is obtained. Between these two models there are intermediate levels.

The procedure of this second stage is similar because it only follows the concept of transforming the PFS model into a MFG model but does not use a top down technique and it does not consider intermediate levels. The C-A net which has a functional and structural perspective, as the PFS model, is transform into a P/T net that has a behavioral perspective, as the MFG model.

In this stage it is used a library that it was previously developed, with established P/T nets for each type of agency. The channel of the C-A net is represented by a place. The global P/T net of the circuit is obtained by replacing all agencies and channels of the C-A net for their P/T net representation. At this level, the components and the relationship among them are preserved and its details are described in a behavioral perspective.

Stage 3: Formalization of expected properties using temporal logic.

The expected properties are described using the natural language. Then temporal logic is applied to formalize these properties, as was explained briefly in section 2.2.

Stage 4: Verification.

This stage has as inputs the P/T net and the property already formalized. Then, the verification is conducted by checking that the design model conforms to the targeted property. Model Checking technique is selected for the verification process. The advantage of this technique is that performs an exhaustive search in the state-space system representation. Other verification processes, such as simulation and testing cover only a limited set of possible

behaviors. Many software tools allow using Model Checking, such as TINA (Berthomieu and Vernadat, 2008) and UPPAAL (Behrmann et al., 2006). If the property is not verified then the design of the circuit must be reviewed.

5. CASE STUDY

The studied case is the circuit shown in Fig. 5a. This circuit was selected due to the number of components that compose it, allowing a simpler explanation of the modeling and for analysis procedure.

Stage 1: Modeling with C-A net.
This stage uses the hydraulic circuit, illustrated in Fig. 5a, to obtain its C-A net representation. Recognize the hydraulic circuit components and the connections among them is the main objective. The circuit and the model are shown in Fig. 11. This C-A net allows identifying active units (the reservoir, the pump & motor/pressure control, the control valve and the actuator) and passive units (connections among them).
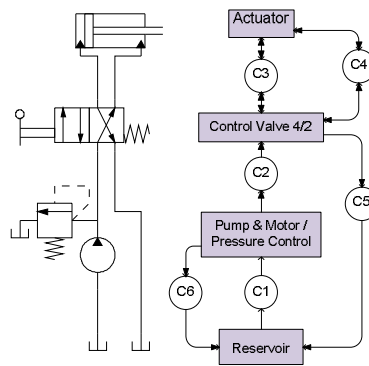

Figure 11. Stage 1. C-A net of the hydraulic circuit.

Stage 2: Modeling with P/T net.
In this stage the C-A net of the circuit, as shown in Fig. 11, is transform into P/T net by using a procedure similar to the PFS/MFG methodology. As explained above, the modeling procedure uses a library to replace each active and passive unit of the C-A net for a specific P/T net representation. In the resultant model, illustrated in Fig.12, can be identified the P/T net for each active unit (the reservoir, the pump & motor/pressure control, the control valve and the actuator) and passive unit.
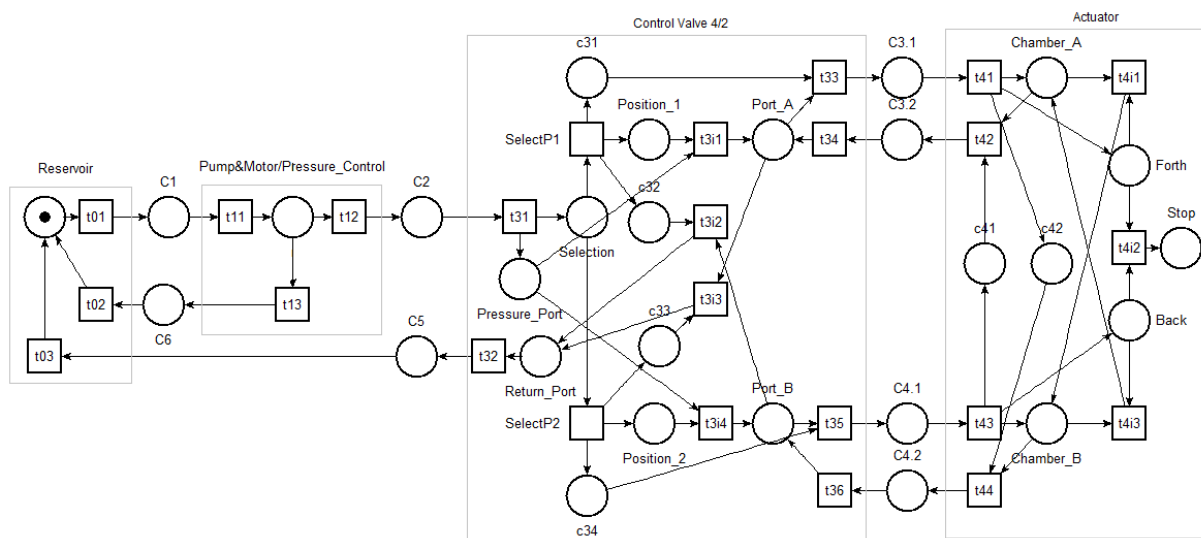

Figure 12. Stage 2. P/T net of the hydraulic circuit.

Stage 3: Formalization of expected properties using temporal logic.
The properties that must accomplish the circuit of Fig. 5a are the following:

First property: For all situations, when the valve is activated (state "Position_1") then in the future the cylinder moves forward (state "Forth").

Second property: For all situations, when the valve is disabled (state "Position_2") then in the future the cylinder moves backward (state "Back").

The properties above can be described using temporal logic as was explained in section 2.2.

First property: G (Position_1=> F Forth)

Second property: G (Position_2=> F Back)

Stage 4: Verification.

Finally, to analyze if the properties are fulfilled in the model, it is applied the Model Checking technique. The TINA software tool is used to verify these properties. The TINA software gives the following results:

For the first property:

```
[] (Position_1 => <> Forth);
TRUE
```

For the second property:

```
[] (Position_2 => <> Back);
TRUE
```

Therefore, these properties allow verifying that the behavior of this circuit is the desired. Whenever the valve is activated, the cylinder moves forward and always the valve is disabled the cylinder returns.

6. CONCLUSIONS

The present paper discusses a procedure to obtain models of hydraulic circuits using Petri nets and its interpretations, such as C-A nets and PFS/MFG methodology.

This procedure allows that every component and connection of the circuit can be identified in the final model. Finally, it is verified if some properties are satisfied by the system under consideration. For this last stage, it uses the Model Checking technique. This technique is used because it performs an exhaustive search in the state-space system representation. Other verification processes are not exhaustive procedures, such as simulation and testing, because they cover only a restrict set of possible behaviors.

The case study is simple but it is sufficient to explain the proposed procedure and the result is satisfactory because it is able to verify if the properties are achieved or not. It is important to mention that in complex hydraulic circuits the probability of making a mistake during the design process is higher. In consequence, it is important to develop methods of modeling and analysis helping to identify if the system is able to achieve its global function or not.

7. REFERENCES

Baier, C, Katoen, J.P., 2008. *Principles of model checking*. The MIT Press.

Behrmann G.; David, A. and Larsen, K., 2006. *A Tutorial on UPPAAL 4.0.* Department of Computer Science, Aalborg University, Denmark.

Belan H. C., 2007. *Formalização da Rede de Petri Canal-Agência para Projeto de Equipamentos Industriais.* Dissertação de mestrado, Universidad Federal de Santa Catarina, Santa Catarina, Brazil.

Berthomieu B. And Vernadat F., 2008. *Time Petri Nets Analysis with TINA toolbox.* CNRS/LAAS –Université de Toulouse, France.

Clarke, E., 2008. *The birth of Model Checking.* Carnegie Mellon University.

Clarke, E., Grumberg, O. and Peled, D., 1999. *ModelChecking.* The MIT Press.

Cvijanovic, D., 2011. *Model Checking.* Retrieved May 25, 2013, from the World Wide Web: URL http://www0.cs.ucl.ac.uk/staff/ucacwxe/lectures/3C05-02-03/aswe17-essay.pdf

Diaz, M, 2010. *Petri Nets: Fundamental Models, Verification and Applications.* Ed. John Wiley & Sons.

De Negri, V. J., 1996. *Estruturação da modelagem de sistemas automáticos e sua aplicação a um banco de testes para sistemas hidráulicos.* Tese de doutorado, Universidad Federal de Santa Catarina, Santa Catarina, Brasil.

De Negri, V. J. and Santos, E. A. P., 2007, *Projeto de sistemas de automação da manufatura.* In: Aguirre, L. A. et al., Enciclopédia de Automática: Controle e Automação, Vol. 1, Ed. Edgard Blucher, São Paulo, Brasil. Chapter 15, pp. 382-417.

Farines J. M., 2012, *Verificação de sistemas.* Apostila (PGEAS) – Universidade Federal de Santa Catarina, Santa Catarina, Brasil.

Gustin, G. B., 1999b, *Aplicação de redes de Petri interpretadas na modelagem de sistemas de elevadores em edifícios inteligentes*, Dissertação de mestrado, Universidade de São Paulo, São Paulo, Brasil.

Hasegawa, K.; Takahashi, K.; Miyagi, P. E., 1988. *Application of the Mark Flow Graph to represent discrete event production systems and system control.* Transactions of the Society of Instrument and Control Engineers, vol. 24, n.1, pp.67-75.

Henke, R, 1970. *Introduction to fluid power circuits and systems.* Addison-Wesley Publishing Company.

Imagine, 2000, "AMESim" - A Brief Technical Overview", Technical Bulletin no. 100, IMAGINE S.A., Roanne, France, available at: www.amesim.com.

Linsingen, I. von, 2008. *Fundamentos de Sistemas Hidraulicos*. Florianópolis: Editora da UFSC.

Miyagi, P.E., 1996, *Controle Programável*, Editora Edgard Blücher, São Paulo, Brasil.

Miyagi, P. E.; Kagohara M. Y.; Junqueira, F.; Riascos, L. A. M., 1999, *Metodologia PFS/MFG para a automação balanceada de sistemas de produção enxuta.* 4º Simpósio Brasileiro de Automação Inteligente, São Paulo, Brasil.

Murata, T. *Petri Nets - Properties, Analysis and Applications.* IEEE, Proceedings. Vol. 77, Nº4, 1989.

Reisig, W., 1992, "A primer in Petri Net design", Berlin: Springer-Verlag, 120 p.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.