DISCRETE CONTROLLERS ANALYSIS USING MODELICA MODELING LANGUAGE AND HYBRID PLANT BEHAVIOUR MODELS: A CASE STUDY

José Machado, jmachado@dem.uminho.pt
Eurico Seabra, eseabra@dem.uminho.pt
University of Minho, Mechanical Engineering Department, CT2M Research Centre, Campus of Azurém, 4800-058 Guimarães, Portugal.

Abstract. *The design of mechatronic systems requires three fundamental aspects when it is intended the reduction of production costs and, consequently, the reduction of the manufacturing time cycle: the controller design, the plant design and optimization of the closed-loop global system controller/plant. Economic aspects applied to mechatronic systems behavior are crucial and may be considered since the design of those systems. Modeling languages, software tools and analysis techniques are, thus, key issues for achieving the proposed goals for obtaining optimized systems, in order to reducing production time consuming and, consequently, reducing production cost by reducing effective production time cycle during normal or desired (and possible undesired) behavior of those systems. In this paper it is presented an approach that intends to reduce the time cycle consuming of mechatronic systems - since the specification and design steps - by using, together, the Simulation analysis technique, the Modelica modeling language and the DYMOLA Simulation environment software. It is also discussed, in a case study, the possibility of using this language for modeling an automation system (controller and plant) in closed-loop behavior. The impact of Simulation tasks in obtaining an optimized behavior is showed and all the considered aspects are extrapolated for manufacturing mechatronic systems of the same kind.*

Keywords*: Mechatronic Systems Design; Modelica Modeling Language, Simulation; Plant Modeling, Controller Modeling*

1. INTRODUCTION

There is a rapidly increasing use of computer simulations in industry to optimize products, to reduce product development costs and time by design optimization, and to train operators. Whereas in the past it was considered sufficient to simulate subsystems separately, the current trend is to simulate increasingly complex physical systems composed by subsystems from multiple domains.

In such complex industrial process, simulation tools are extremely useful since they can contribute to higher product quality and production efficiency in several ways. For example, modifications in a plant could be tested (both statistically and dynamically) in advance in a simulator saving much of the trial and error procedure that is used nowadays; the optimization of plant behavior parameters can be performed too. Besides, a dynamic simulator of the plant and of its control would allow for a thorough study of different control strategies, and would be an efficient way to tune controllers for new equipments. Finally, a simulation tool can also be a way of training not only the operators but also the production engineers and technicians. Some tools have been developed in order to simulate the behavior of automation systems (Fig. 1).

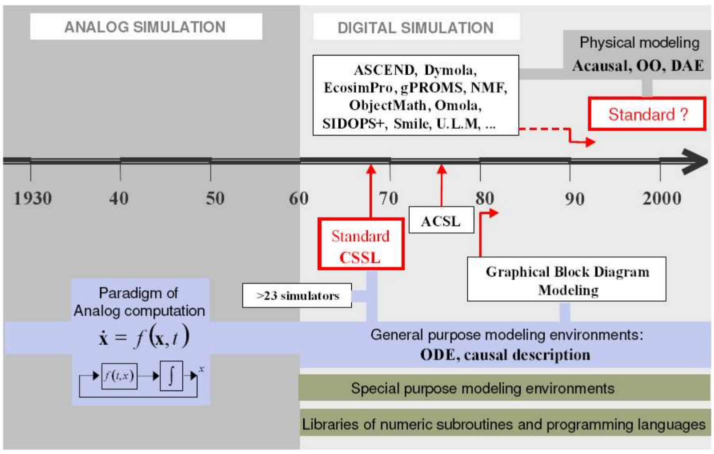

Figure 1. Evolution of modeling and simulation tools (Martin, 2007).

Graphical block diagram modeling is widely used in control engineering (Karayanakis, 1995). Some examples of languages and environments supporting this paradigm are Matlab/Simulink (Matlab, 2011), MATRIXX/SystemBuild (Matrixx, 2011), HYBRSIM (Mosterman, 2002) and ACSL Graphics Modeller (MGA Software 1996). Block diagram modeling paradigm might be considered as a heritage of analog simulation (Aström et al. 1998).

On the other hand, object-oriented modeling languages and compilers supporting the physical modeling paradigm have become available since the 1990's decade. This is driven by demands from users to be able to simulate complex multi-domain models.

The fundamentals of planning an industrial process in a numerically controlled environment lie with the control and quality of operation planning and that planning time represents 50 to 80 percent of the global process time for single parts or small batches (Ahlquist, 2002). It becomes more critical for complex situations and new manufacturing technologies tend to extend the time further. Process planning has been defined by Alting (1989) as a function within the manufacturing environment which deals with the selection of manufacturing processes and parameters to be used to create the final product (Alting and Zhang, 1989).

Investigations by Younis (1997) showed that an efficient CAPP system could result in reduction of the manufacturing costs by up to 30% and would also reduce the manufacturing cycle and the total engineering time by up to 50% (Younis and Wahab, 1997). Hence, the focus has been on process planning as the task of the determination of manufacturing processes, which for instance can determine whether or not a product should be manufactured through a defined operation (ISO, 2004).

In this paper it is presented a methodology for design automated manufacturing systems with modeling of controller, plant and interaction between them in order to guarantee the correct behavior of the system and, also, to reduce the manufacturing time cycle. For accomplish these goals there are used the Simulation technique (Baresi et al., 2000) (Baresi et al., 2002), the Modelica modeling language (Fritzson et al. 1998) (Elmqvist et al. 1999) (Fritzson and Bunus, 2002) and Dymola software (Dymola, 2011). The Modelica language and its associated support technologies have achieved considerable success through the development of specific libraries and allows modeling the plant, even considering simulation of different kind of systems technologies (hydraulic, pneumatic, HAVAC, electrical,…) and also the modeling the controller using the Stategraph library (Otter et al., 2005).

Modelica supports both high level modeling by composition and detailed library component modeling by equations. Models of standard components are typically available in model libraries. Using a graphical model editor, a model can be defined by drawing a composition diagram (also called schematics).

With the use of this approach it is possible to simulate the desired behavior, the possible unexpected behavior for the system - because it is developed a global model of the system (controller model, plant model and respective closed-loop behavior) – and, finally, to study and to define the conditions that will allow to reduce considerably the manufacturing time cycle, fixing some process parameters and allowing the changing of other process parameters.

The consideration of the Controller Modeling, the Plant Modeling and also the interaction (controller-plant) model, can make Simulation tasks more realistic and more conclusive (Dymola, 2011) (AS, 2011) (Mosterman, 2002) (Baresi, 2002).

To accomplish our goals, in this work, the paper is organized as follows. In Section 1, it is presented the challenge proposed to achieve. Section 2 presents the case study involving a tank filling/emptying system. Further, in section 3, it is presented the methodology to obtain the plant model, namely the conditions of functioning and the definitions of the different stages, parameters and variables considered in this task (mathematical modeling). Section 4 is exclusively dedicated to the closed-loop (controller + plant) system modeling, using the Modelica modeling language. Section 5 presents and discusses the obtained results on simulation, performed with Modelica Language, considering system behavior and, also, optimization of the manufacturing time cycle. Finally, in Section 6, the main conclusions and future work are presented.

2. CASE STUDY

The case study that is proposed as base for this work is inspired on the benchmark system proposed by (Kowalewski et al., 2001).

Figure 2 illustrates an example of an evaporator system, which consists of two tanks, where an aqueous solution suffers transformations. In the first tank that solution should acquire a certain concentration through the heating of the solution using an electrical resistance (H1) which provokes the steam formation.

Associated to the tank1 (tank1) a exists a condenser (C) responsible for the condensation of the steam that however it was formed. The cooling, in that condenser, it is done through the circulation of a cooling liquid (whose flow is measured by sensor FIS) that passes through the cooling circuit (if open the valve V13).

Associate to the tank1 there are a group of sensors: level sensors (maximum (LIS1) and minimum (LII1)), temperature sensor (acceptable maximum (TIS1)); sensor of conductivity (QIS) that is to indicate the intended concentration; they also exist several actuators: filling valve of the tank1 (V12), drain valve (V16) and emptying valve (V15), that it is also the filling valve of the tank2.

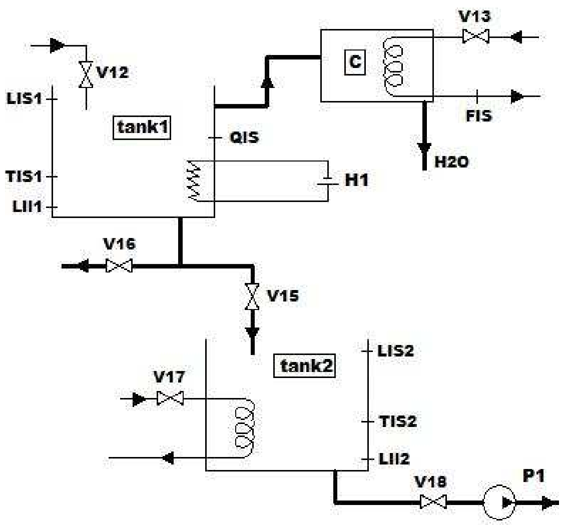

Figure 2. Scheme of the entire evaporator system

In the normal operation mode, the system works as follows.

The tank1 should be previously filled to its superior level with an aqueous solution by opening valve V12. When the tank1 is full, the heating system is switch on and also, in simultaneous, the cooling system of the condenser by opening valve V13. When it is formed steam, this condenses in the condenser C. When the concentration desired in the tank1 is reached, there are switch off the heating system and the cooling system of the condenser. Continuously the solution flows from tank1 into tank2, and it must be guaranteed that the tank2 is empty.

The transfer of the solution to the tank2 is for a powder-processing operation that is not, here, described. For that powder-processing operation, there is necessary to heat the solution to avoid possible crystallization, and for that there are two approaches: it can heat until the temperature sensor of the tank2 indicates that the desired temperature was reached; or it can heat up for a certain time. Finally, the tank2 is emptied by the pump P1, if the valve V18 be opened.

On the other hand, in the possible unexpected operation mode, the system works as follows.

A possible unexpected scenario of the system happens when the cooling fluid flow in the condenser be to low (detected by sensor FIS). This implicates the increase of pressure and temperature in condenser C and tank1, if the heating system keep switch on (solution steam). It is necessary to guarantee that the pressure in the condenser C doesn't exceed a maximum value to avoid its explosion. For that, it should be guaranteed that the heating in the tank1 is switch off before the open of the safety valve (V16).

For this situation of unexpected operation, it should switch off the resistance H1 the more quickly possible, but tends in account that the solution doesn't crystallize, then that we are before a critical time. To switch off the resistance H1 they are considered two possibilities: through a time after sensor FIS to have detected reduced flow; or through the sensor of temperature TIS1 (due to the pressure and temperature are parameters that are directly related).

There are evidences that should be guaranteed, as for instance that the tanks should never overflow. After the unexpected situation occurs, all of the valves should be immediately closed.

2.1. Controller specification by SFC (IEC 60848)

In order to guarantee the desired behavior, the controller specification was developed according to IEC 60848 SFC specification.

The input and output variables of the controller which controls the process in closed-loop are presented and described in Tab. 1.

The SFC specification of the controller behavior (normal and unexpected modes) is presented in Fig 3.

The controller specification was directly translated to Modelica modeling language, more specifically to the library for hierarchical state machines StateGraph (Otter et al., 2005).

Table 1. Input/Output variables of the controller model.

Inputs	Outputs
LIS1 – Superior level of the tank1	V12 – Solution entrance of the tank1
LII1 – Inferior level of the tank1	V13 – Cooling of the condenser
QIS – Electrical conductivity of the solution in tank1 (concentration)	V15 – Valve of solution passage of the tank1 for the tank2
TAlarm– Maximum solution temperature in tank1 (sensor T1S1)	V16 – Drain of the tank1
LIS2 – Superior level of tank2	V17 – Heating of the tank2
LII2 – Inferior level of tank2	V18 – Emptying of the tank2
TIS2 – Solution temperature in tank2	P1 – Emptying pump of the tank2
FIS – Cooling solution flow of the condenser C	H1 – Heating Resistance of the tank1

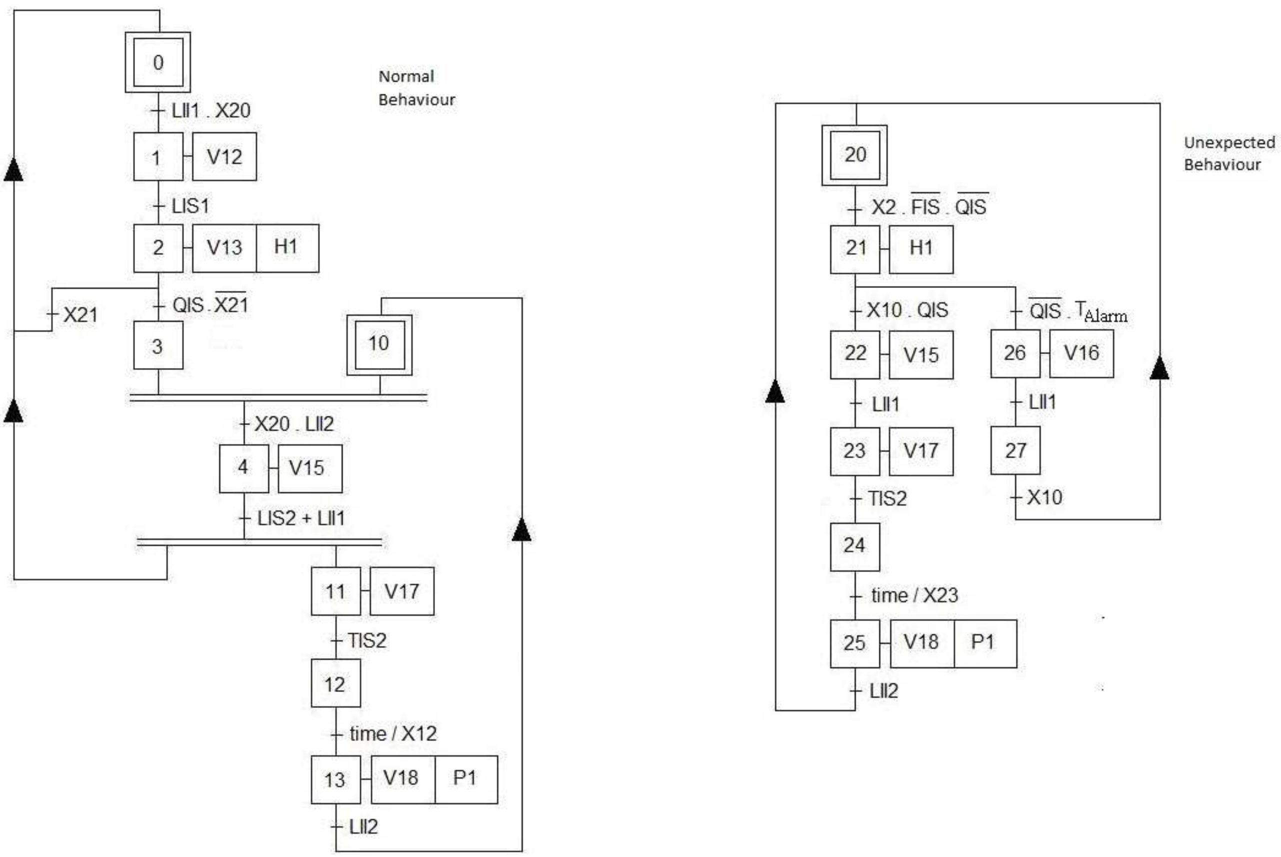

Figure 3. SFC controller specification: normal and unexpected behavior modes.

3. PLANT MODELING

The set of plant model equations is presented in Tab. 2.

Table 2. Algebraic and Deferential equations concerning the Plant Model.

Stage 1 *Heating while T2 is drained*	$(dQ/dt) = Q_{Heat} - Q_{Loss} - Q_{Evap}$ $\frac{dH_1}{dt} = 0$; $\frac{dH_2}{dt} = -K_1\sqrt{H_2}$ $(dQ/dt) = d(T.c_{p,L}.(m_L + m_V))/dt$; $Q_{Loss} = kA.(T - T_e)$ $Q_{Evap} = (dm_V/dt).\Delta h_{ev}$; $K_1 = (A_R/A_2).\sqrt{2g}$ $p = a_0 + a_1 T + a_2 T^2$ *(boiling pressure, dissolve substance ignored)* $pV_V = (m_V/M_L)R_m T$; $\Delta h_{ev} = b_1 + b_2 T$ $m_{total} = m_L + m_V = 6$ *kg (total mass of fluid),* *QHeat (heat supply rate)* $V_V = 0.02m^3$ *(vapor volume, assumed to be constant),* $kA = 24W/K$ *(heat loss flow per Kelvin)*
Stage 2 *Cooling while T2 is drained*	$(dQ/dt) = -Q_{Loss} - Q_{Evap}$ $\frac{dH_1}{dt} = 0$; $\frac{dH_2}{dt} = -K_1\sqrt{H_2}$ T < 373K: $(dQ/dt) = d(T.c_{p,L.}.m_L)/dt$; $Q_{Evap} \cong 0$ $T > 373K$, $p > 1bar$: $(dQ/dt) = d(T.c_{p,L.}.(m_L + m_V))/dt$; $Q_{Evap} = (dm_V/dt).\Delta h_{ev}$; $Q_{Loss} = kA.(T - T_e)$ $kA = 22.5W/K$ *(heat loss flow per Kelvin)* *Note: In this stage it will be used the same algebraic equations and parameters as in stage 1.*
Stage 3 *Cooling while T1 is drained*	$(dQ/dt) = -Q_{Loss}$ $\frac{dH_1}{dt} = -K_2\sqrt{H1}$; $\frac{dH_2}{dt} = -K_1\sqrt{H_1}$ $(dQ/dt) = c_{p,L.}.(dT/m_L)/dt$; $Q_{Loss} = kA.(T - T_e)$ $K_2 = (A_R/A_1).\sqrt{2g}$; $m_L = \rho_L H_1 A_1$; $A = A_1 + \pi.DH_1$ $k = 150W/K/m^2$ *(heat loss transfer coefficient),* A_1 =0.03m^2, A_2 =0.06m^2*(cross-sectional area* T1 and T2*)*
Variables	state: T *(temperature in* T1*)*, H_1, H_2 *(liquid heights, tanks considered empty when* $H_{1/2} \le 0.0017m$ *)* algebraic: m_L *(liquid mass)*, m_V *(vapor mass),* Δh_{ev} *(evaporation enthalpy), p (pressure), A (heat loss area)*
Additional parameters	A_1 =0.03*m2*, A_2 =0.06m^2 *(cross-sectional areas of* T1 *and* T2 *)*, $A_R = 2.10^{-5}m^2$ *(pipe cross-sectional area)* $a_0 = 9.3 \cdot 10^6 N/m^2$, $a_1 = -5.28 \cdot 10^4 N/m^2/K^2$, $a_2 = 75.4N/m^2/K^2$ ($a_0, a_1, a2$ *pressure constants),* $b_1 = 3.294 \cdot 10^6 J/kg$, $b_2 = -2.78 \cdot 10^3$ J/kg/K *(enthalpy constant),* $c_{p,L} = 4220J/kg/K$ *(liquid heat capacity),* $D = 0.2m$ *(diameter of* T1*)*, $g = 9.81m/s^2$ *(gravity constant),* $M_L = 0.018kg/mol$ *(molecular weight of liquid),* $\rho_L = 970kg/m^3$ *(liquid density),* $R_m = 8.314J/kg/mol$ *(molecular gas constant),* $T_e = 283K$ *(environment temperature)*

The plant modeling has two goals: first to assure that the controller specification is adequate for the intended system behavior and, second, to minimize the cycle time for repetitive automation systems processes. In this paper there are discussed the two of them: to be sure that the system behaves as expected – without leading to dangerous situations - and to maximize the productivity of the process; it implicates the maximization of the number of batches being processed in the process in parallel in tank1 and tank2.

For that, it was developed a hybrid model with three stages for the evaporation process.

In this model it was considered the pressure increasing in the evaporator (tank1) during the time that the heating is switched on (process stage 1).

The resulting solution concentration depends on the mass of water that is evaporated in consequence of the temperature increasing. The evolution to stage 2 happens when the alarm temperature TAlarm is achieved (in agreement to Fig. 3). In this stage, categorized by a temperature decreasing, two different approaches were used, respectively, for temperature T below or above the boiling water point (373 K). Finally, for the last stage considered (stage 3), that is obtained when the tank2 (T2) is empty, the heat loss is the only significant term of the heat balance; it promotes a continuous slow decreasing of temperature.

Due to discrete switching between the two different continuous systems (T1 and T2), which happens not only at the stage transitions, by changing the position of the on/off valves (V15 and V18), but also in stage 2 for boiling water point, this developed model is of hybrid nature. The main required parameters and algebraic equations are presented in detail in the Tab. 2.

The setting of alarm temperature TAlarm is chosen correctly to accomplish the following two opposed very important properties: On the one hand it must be low enough to avoid a dangerous temperature and pressure values, and on the other hand it has to be sufficient high so that temperature T does not fall below a crystallization temperature before liquid level in tank1 (H1) becomes zero.

4. SYSTEM MODELED USING MODELICA LANGUAGE

Modelica is a powerful programming language where equations are used for modeling of the physical phenomena. No particular variable needs to be solved for manually because the software Dymola (Dymola, 2011) has enough information to decide that automatically. This is an important property of Dymola to enable handling of large models having more than hundred thousand equations.

Due to the described potentialities, it was developed a global model of the evaporator system, already presented in the previous sections. The plant and the controller specification were modeled using the Dymola software and the object-oriented programming language Modelica (Fritzson and Vadim, 1998) (Elmqvist and Mattson, 1997). Additionally, to model the controller, it was used the library for hierarchical state machines StateGraph (Otter et al., 2005), which are included in the Dymola software.

Related with the plant part, it was modelled the filling source, the tank1 and tank2, the heater (H1), the condenser and the valves. For that, there were used the parameters and algebraic equations presented in the Tab. 2.

On the other hand, the controller model was developed according the SFC specifications (see Fig. 3).

Figure 4 presents the schematic representation of the global system model in modelica modeling language.

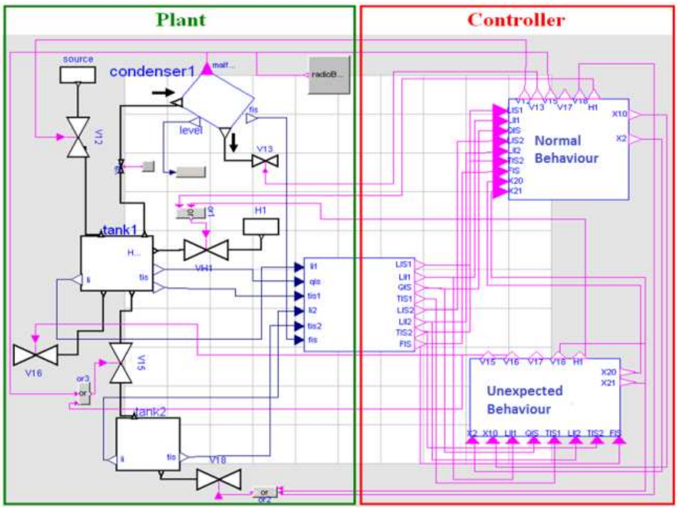

Figure 4. Schematic representation of the system, using Dymola software and Modelica modelling language.

Also, due to the reason of being specified a discrete controller, to control the hybrid plant, it was necessary to implement an appropriate interface, that allows translating the analog outputs signals of the plant (tanks levels, temperatures, concentration,…) to digital signals. These signals are used as inputs of the discrete controller model.

5. RESULTS OBTAINED BY SIMULTION

In this section, there are presented results of simulations that were accomplished with the purpose of studying the dynamical behavior of the hybrid models described in the previous sections in order to maximize the productivity of the process that it implicates the maximization of the number of batches being processed in the process in parallel in tank1 and tank2. Also, the normal and unexpected system's behavior were simulated.

Moreover, these simulations can be seen as a "system preliminary analysis" to check if the system behaves in agreement to a given specification for a particular case, like as, a given a initial state of the process and a given control program. However, it must to be enhanced that this is not verification in the strict sense, since it relies on the appropriate selection of the considered cases.

In order to perform the hybrid model simulation with different heating powers it was necessary to define the parameters: start and stop time of the simulation, the interval output length or number of output intervals and the integration algorithm. In the present work, in all simulations performed, the Dassl algorithm (Basu et al., 2006) with 1000 output intervals was used.

The first simulation performed was devoted to verify if the SFC of the controller system (see Fig. 3) modelled with Modelica language with the library for hierarchical state machines StateGraph simulated correctly the evaporator system, in their normal operation.

Figure 5 shows results of the simulation without the occurrence of the condenser malfunction during the production cycle, which corresponds to the normal operation, considering the level of the tanks.

Observing Fig. 5 it can be concluded that the system is properly simulated by the developed Modelica model, since the two main properties that are important to prove are confirmed, for instance, the drainage of the solution, present in the tank 1, only happens when the tank2 is empty and, also, the filling of the tank1 happens soon after itself is empty.

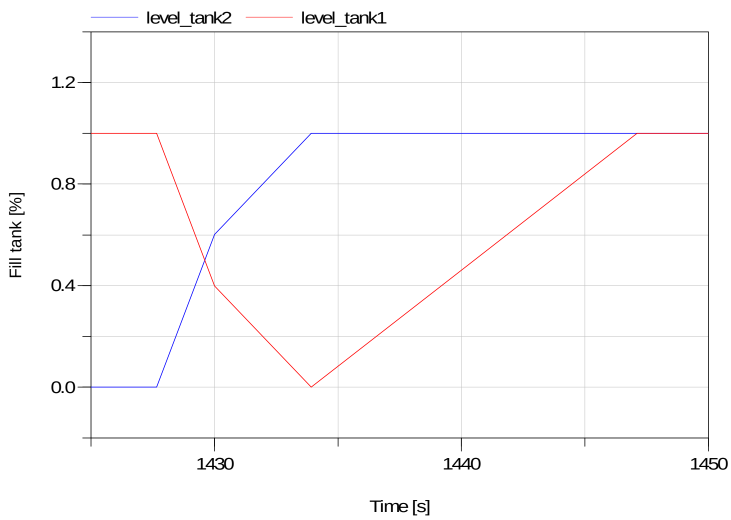

Figure 5. Level of tanks in function of time in normal operation of the evaporator system.

After being concluded that the normal operation behaviour is properly simulated by the proposed program there were performed other simulations in order to obtain the relationship between several physical process parameters that can maximize the number of batches in the evaporator system.

The batches number optimization depends on the best synchronism that happens among the time in that the solution present in the tank1 is prepared to be drained and the time in that the tank2 finishes its emptying, because it implicates less wastes of time in the process.

Among of several physical variables of the process (see Tab. 2) it was chosen the heat supply rate (QHeat) because it is the most relevant variable that determine the rate of the steam formation (this condenses in the condenser C) and correspondingly, the time in that the solution present in the evaporator (tank1) is prepared to be drained (desired concentration reached).

In addition, in all of the performed simulations, it was assumed a time of 200s for the solution powder-processing operation fulfilled in the tank2.

Figures 6 and 7 illustrate the behavior of the model given in the Tab. 2, respectively for heat supply rate (QHeat) of 2500W and 3170W.

Analyzing Fig. 6 it can be stated that it happens a great synchronism lack between the time in that the solution present in the tank1 is prepared to be drained and the time in that the tank2 finishes its emptying. Also, it can be concluded that using a heat supply rate of 2500W it will lead to a waste of time in the process about 300s.

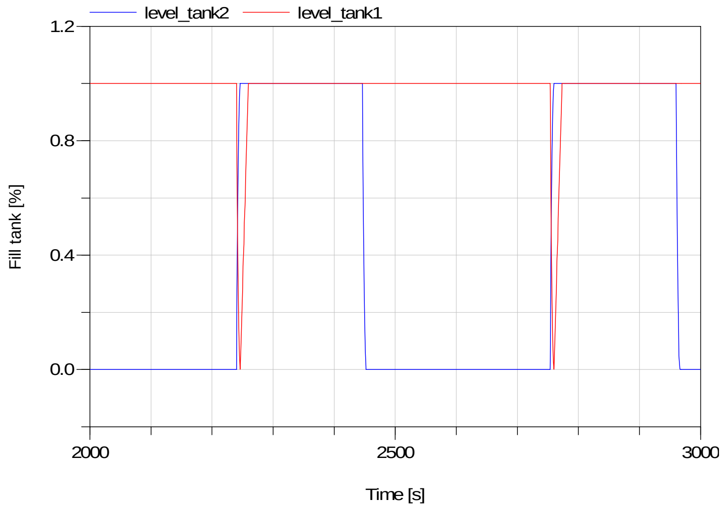

Figure 6. Level tanks in function of time with a heat supply rate of 2500W.

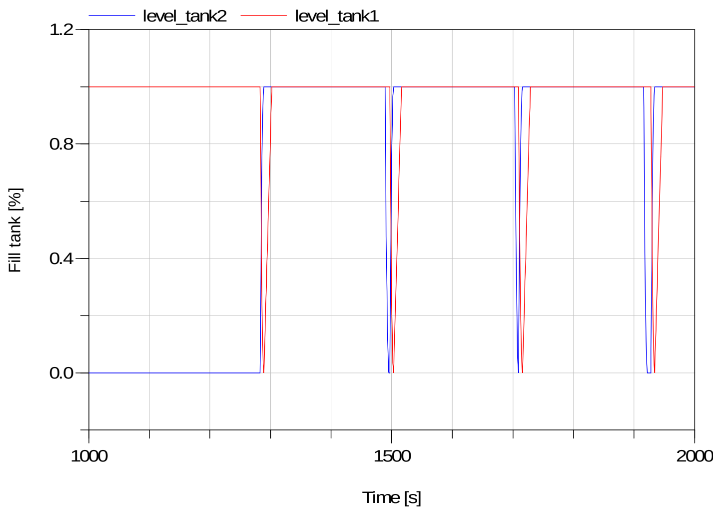

Figure 7. Level tanks in function of time with a heat supply rate of 3170W.

Otherwise, observing Fig. 7 it can be verified the synchronism that occurs among the time in that the solution present in the tank1 is prepared to be drained and the time in that the tank2 finishes its emptying.

An excellent synchronization can be confirmed in the Fig. 8, which presents in detail the simulation results for the time period when takes place the transfer of the solution between tank1 and tank2, because wastes of time don't exist in the process. This manner, in agreement with the simulations results presented, it can be concluded that the heat supply rate of 3170W is the most appropriate to obtain the optimization of the number of batches in the evaporator system, considering the values of the physical variables of the process presented in Tab. 2.

In order to be possible to generalize the batches optimization - that it implicates the productivity maximization of the evaporator system - it is essential to know the optimized relation between the heat supply rate and the time for the solution powder-processing operation fulfilled in the tank2.

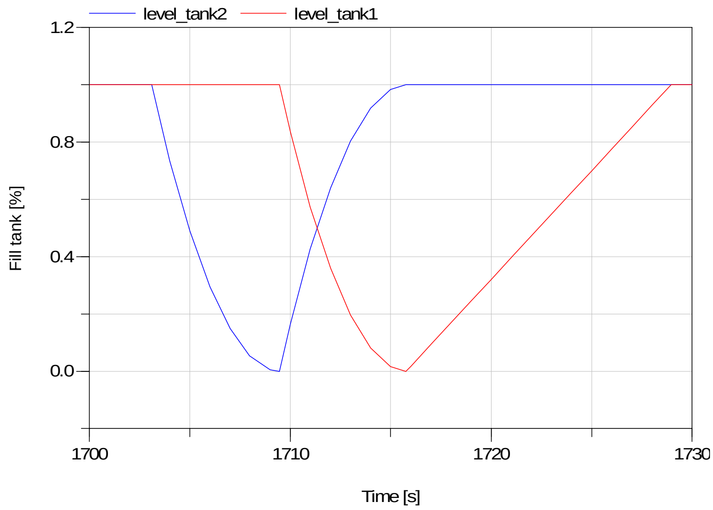

Figure 8. Level tanks in function of time with a heat supply rate of 3170W for the solution transfer time period between tank1 and tank2.

Figure 9 shows the optimized time for the solution powder-processing operation fulfilled in the tank2 in function of heat supply rate, as example, from 2500 to 3170W.

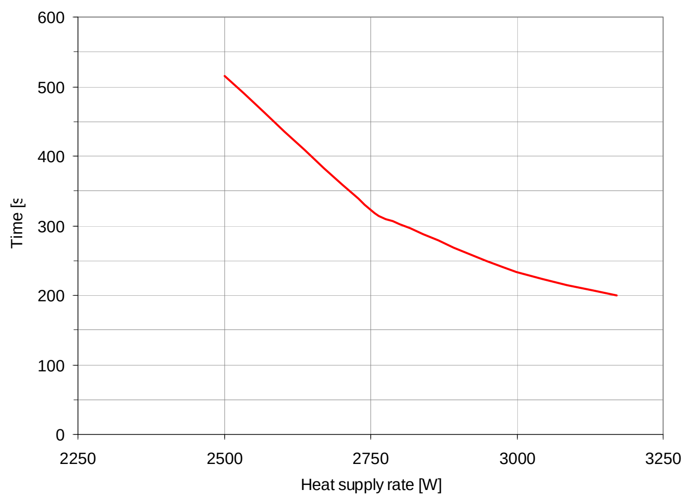

Figure 9. Time for the solution powder-processing operation fulfilled in the tank2 in function of heat supply rate.

It can be concluded, analyzing Fig. 9, that the increase of the heat supply rate originates a very significant decrease on the time available for the solution powder-processing operation fulfilled in the tank2. It can be highlighted that the more accentuated time reduction happens in the interval from 2500 to 2750 W.

6. CONCLUSIONS AND FUTURE WORK

Modelica modeling language is a strong solution in order to perform software-in-the-loop simulation. It allows connecting different technologies in an only simulation environment and deal with complex hybrid plant models.

The present research proved to be successful using the Modelica modeling Language to obtain a system (controller and plant) model and using it, in a closed-loop behavior, in order to achieve two main goals: first, to be sure about the controller behavior (normal and unexpected modes) and, second, to reduce the manufacturing time cycle for the manufacturing mechatronic system.

Some parameters and functional aspects of the system - that have been simulated helping defining a set of values of different variables, in order to obtain lower time cycles considering that the system is repetitive - were presented. The reduction of costs is effective and useful. The used technique is adequate to obtain good solutions concerning manufacturing mechatronic systems design.

As future work the authors will use hardware-in-the-loop simulation, in order to obtain stronger results concerning controller dependability.

7. REFERENCES

Ahlquist F. (2002). “A Methodology for Operation Planning”, in Department of Mechanical Engineering Lund, Sweden: Lund University, p. 89.

Alting, L., and Zhang, H. (1989). “Computer aided process planning: A state of the art survey”, International Journal of Production Research, vol. 27, pp. 553-585.

AS (2011). “Automation Studio software”. Available in: http://www.automationstudio.com/ (acceded in Jan 21st, 2011).

Aström, K. J., Elmqvist, H. & Mattsson, S. E., (1998). “Evolution of continuous time modeling and simulation”, in Proceedings of the 12th European Simulation Multiconference, Manchester, UK, pp. 9–18.

Baresi L., Mauri M., Monti A., Pezzè M. (2000) “PLCTOOLS: Design, Formal Validation, and Code Generation for Programmable Controllers”. Special Session at IEEE Conference on Systems, Man, and Cybernetics. Nashville USA.

Baresi L., Mauri M., Pezzè M. (2002) “PLCTools: Graph Transformation Meets PLC Design”, Electronic Notes in Theoretical Computer Science 72 No. 2.

Basu S., Pollack R., Roy M. (2006). “Algorithms in Real Algebraic Geometry”, In Springer (Eds), Algorithms and Computation in Mathematics, (10), 2ªedition, 2006.

Dymola (2011). Available in: http://www.3ds.com/products/catia/portfolio/dymola (acceded in Jan 25th, 2011).

Elmqvist, Hilding, Mattsson S., Otter M. (1999) “Modelica - A language for physical system modeling”, Proceedings of the IEEE Symposium on Computer-Aided Control System Design. August, Hawaii.

Elmqvist E., Mattson S. (1997) “An Introduction to the Physical Modelling Language Modelica”. Proceedings of the 9th European Simulation Symposium, ESS'97. Passau, Germany.

Fritzson, Peter, Vadim E. (1998) “Modelica, a general object-oriented language for continuous and discrete event system modeling and simulation”, 12th European Conference on Object-Oriented Programming (ECOOP’98). Brussels, Belgium.

Fritzson, Peter, Bunus P. (2002) “Modelica, a general object-oriented language for continuous and discrete event system modelling and simulation”, Proceedings of the 35th Annual Simulation Symposium. April, San Diego, CA.

Karayanakis, N. M., (1995). “Advanced System Modelling and Simulation with Block Diagram Languages”, CRC Press, Inc.

Kowalewski S., Stursberg O. and Bauer N. (2004) “An Experimental Batch Plant as a Test Case for the Verication of Hybrid Systems”. European Journal of Control. vol. 7, n_4, pp. 400-415, 2001.

ISO (2004). International Standard 14649-12: Part 12 : Industrial automation system and integration - Physical device control - Data model for computerized numerical controllers.

Martin, C. V. (2007) “Object-Oriented Modeling of Virtual Laboratories for Control Education”. PhD Thesis, Universidad Nacional de Educación a Distancia, Escuela Técnica Superior de Ingeniería Informática, Departamento de Informática y Automática, Madrid, Spain.

Matlab (2011). Matlab Available in http://www.Mathworks.com (acceded in March 04th, 2011).

MATRIXX (2011). MATRIXX Available in http://www.ni.com/matrixx (acceded in March 04th, 2011).

MGA Software, 1996. ACSL Graphic Modeller - Version 4.1, MGA Software.

Mosterman P. J. HYBRSIM (2002) “A modeling and simulation environment for hybrid bond graphs”. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering. Vol. 216, N 1, pp 35-46.

Otter M., Årzén K., Dressler I. (2005) “StateGraph - A Modelica Library for Hierarchical State Machines”, Modelica 2005 Proceedings.

Younis, M. A. and Wahab, A.M.A. (1997) “A CAPP Expert System for rotational components”, Computers and Industrial Engineering, vol. 33, pp. 509-512, 1997.

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