# Techniques for Modeling Discrete Controllers for the Optimization of Hybrid Plants: a Case Study

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***Abstract*** — *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 operator. Whereas in the past it was considered sufficient to simulate subsystems separately, the current trend is to simulate increasingly complex physical systems composed of subsystems from multiple domains. The domain-specific tools, such as circuit simulators or multibody programs, cannot handle components of other domains in a reasonable way. The gap is traditionally too large between the user's problem and the model description that the simulation program understands. The main objective of this project is to provide to the MSc and Phd graduation students of Mechanical Engineering at the University of Minho a methodology for direct application in the design and manufacture of automated industrial systems. In this manner, the command of those systems can be simulated and tested when the physical part of the machine still does not exist. Therefore the simulation enables the reduction of the production times of automation systems because the manufacture does not need the physical part of the machine to perform tests and simulations of the command of the system. The work herein presented is a part of a larger project, currently being developed by several researchers from different Departments of the School of Engineering from University of Minho (Portugal). The main objective of this project is to develop, implement and provide, in a Web environment, a virtual and remote laboratory applied to the Automation and Control teaching/learning in Engineering: WALC (Web Assisted Laboratory for Control). For this purpose, it will be necessary to develop analysis techniques of industrial controllers, allowing, first, the development of more dependable controllers and, second, the optimization of some parameters related with industrial processes, by modeling and simulating the closed-loop consisted by the plant and the controller. In this paper a case study of a hybrid plant modeling for discrete controller's analyses will be present and discussed. This will be carried out using the specific software Dymola.*

***Index Terms*** —*Competency-based education, Modeling and Simulation Techniques, Automated Systems Teaching.*

## INTRODUCTION

Modeling and simulation are becoming more important since engineers need to analyze increasingly complex systems composed of components from different domains. Current tools are generally weak processing multi-domain models because the general tools are block-oriented and thus demand a huge amount of manual rewriting to get the equations into explicit form. Modeling should be much closer to the way an engineer builds a real system, firstly trying to find standard components like motors, pumps and valves from manufacturers' catalogues with appropriate specifications and interfaces.

In such a 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 in advance (both statistically and dynamically) in a simulator saving much of the trial and error procedure that is used nowadays; the optimization of the plant behavior parameters can also be performed. Besides, a dynamic simulation of the plant and its control would enable a detail study of different control strategies, and would be an efficient way to tune controllers for new equipments area applications. Finally, a simulation tool can also be an important way of training not only for the operators but also for the production engineers and other technicians. Some tools have been developed in order to simulate the behavior of automation systems.

Graphical block diagram modeling is widely used in control engineering [1]. Some examples of languages and environments supporting this paradigm are Matlab/Simulink [2], MATRIXX/SystemBuild [3], HYBRSIM [4] and ACSL Graphics Modeller [5]. Block diagram modeling paradigm might be considered as a heritage of analog simulation [6].

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 the user's demands in order to simulate complex multi-domain models.

In this paper it is presented a case study of a hybrid plant modeling for discrete controllers, showing how the Modelica modeling language can be used to optimize plant behavior parameters in order to guarantee the good and desired behavior for the system, namely, the shorter time cycle, combined with other aspects like energy consumption, for example.

To achieve the proposed goal, the following sections are devoted to the presentation of the Modelica modeling language and the Dymola Simulation environment; the case study which is the base for our study; the discussion of the mathematical modeling of the plant; the presentation of Modelica system model (controller model coupled with plant model); the discussion of the obtained results concerning the defined plant behavior parameters to study and, finally, the presentation of the conclusions.

## MODELICA AND DYMOLA

In recent years, in terms of modeling and simulation research, the concept of object-oriented modeling has achieved a huge relevance. Several works have demonstrated how object-oriented concepts can be successfully employed to support hierarchical structuring, reuse and evolution of large and complex models independent from the application domain and specialized graphical formalism.

To handle complex models, the reuse of standard model components is a key issue. But in order to exchange models between different packages an unified language is needed. Modelica is an object-oriented, general-purpose modeling language that is under development in an international effort to introduce an expressive standardized modeling language [7, 8]. Modelica supports object-oriented modeling using inheritance concepts taken from computer languages such as Simula and C++. It also supports non-causal modeling, meaning that model's terminals do not necessarily have to be assigned an input or output role. In fact, in the last few years it has been proved in several cases that non-causal simulation techniques perform much better than the ordinary object-oriented tools.

Modelica is a powerful programming language where equations are used for modeling of the physical phenomena. No particular variable needs to be solved manually because the software Dymola [9] has enough information to carry out that decision automatically. This is an important feature of Dymola to enable the handling of large models having more than hundred thousand equations. Modelica supports several formalisms: ordinary differential equations (ODE), differential-algebraic equations (DAE), bond graphs, finite state automata, Petri nets, etc.

## CASE STUDY DESCRIPTION

The case study that is proposed in this work is inspired on the benchmark system proposed by Kowalewski *et al*. [10]. Figure 1 illustrates an example of an evaporator system, which consists of two tanks, where an aqueous solution suffers several transformations. In the first tank the solution should acquire a certain concentration through the heating of the solution using an electrical resistance (H1), which causes the steam formation.

Associated to tank1 (Figure 1) the condenser (C) is responsible for the condensation of the steam that was produced. The cooling, in that condenser, is carry out through the circulation of a cooling fluid (whose flow is measured by the sensor FIS) that passes through the cooling circuit (if the valve V13 is opened).

Together with the tank1 there are a group of sensors: level sensors (maximum (LIS1) and minimum (LII1)), temperature sensor (acceptable maximum (TIS1)); sensor of conductivity (QIS), used to indicate the desired solution concentration; there are several actuators: filling valve of the tank1 (V12), drain valve (V16) and the emptying valve (V15), which is also the filling valve of the tank2.

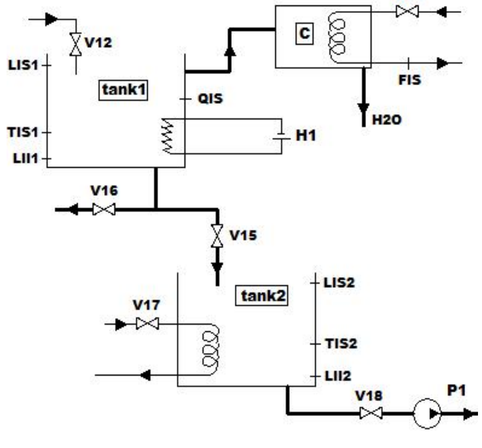


FIGURE 1
SCHEME OF THE ENTIRE EVAPORATOR SYSTEM

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

Tank1 should be previously filled to its top level with an aqueous solution by opening valve V12. When the tank1 is full, the heating system is switched on and simultaneously, the cooling system of the condenser, by opening valve V13. When the steam is produced, it condenses in the condenser C. When the desired concentration in the tank1 is reached, the heating system and the cooling system of the condenser are switch off. The solution flows continuously from tank1 into tank2, having the guarantee that tank2 is empty. The transfer of the solution to tank2 is for a powder-processing operation that is not described here. For that powder-processing operation, it is necessary to heat the solution to avoid possible crystallization; there are two different approaches: it can be heated until the temperature sensor of tank2 indicates that the desired temperature was reached, or it can be heated for a certain time. Finally, tank2 is emptied by the pump P1, if the valve V18 is opened.

On the other hand, in the possible failure operation mode, the system works as follows:

A possible failure scenario happens when the cooling flow in the condenser is to low (detected by the sensor FIS). This implies the increase of pressure and temperature in condenser C and tank1, if the heating system is still working (solution steam). It is necessary to guarantee that the pressure in the condenser C does not exceed a maximum value to avoid an explosion. For that reason, it should be guaranteed that the heating in tank1 is switched off before the opening of the safety valve (V16). For this situation of failure operation, the resistance H1 should be switched off as quickly as possible, taking into account that the solution does not crystallize, which corresponds to a critical time. To switch off the resistance H1, two possibilities are considered: during the time that the sensor FIS have detected a reduced flow, or with the temperature sensor TIS1 (due to the pressure and temperature).

Other facts should also be guaranteed, as the fact that the tanks should never overflow. When the failure situation occurs, all of the valves should be immediately closed.

## Controller Specification

In order to guarantee the desired behavior, the controller specification was developed according to the IEC 60848 SFC specification. The input and output variables of the controller, which controls the process in closed-loop, are presented and described in Table 1. The SFC specification of the controller behavior (normal and failure modes) is presented in Figure 2.

| 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 C |
| QIS – Electrical conductivity of the solution in tank1 (concentration) | V15 – Valve of solution passage of the tank1 for the tank2 |
| $T_{Alarm}$– 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 |

TABLE 1
INPUT/OUTPUT VARIABLES OF THE CONTROLLER

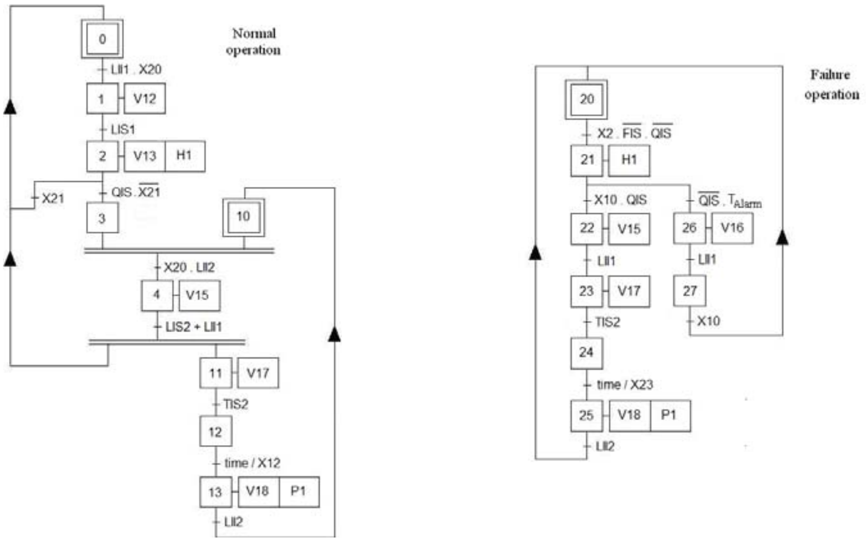


FIGURE 2
SFC SPECIFICATION OF THE CONTROLLER – NORMAL OPERATION MODE AND FAILURE OPERATION MODE

The controller specification was directly translated to Modelica modeling language, more specifically to the library for hierarchical state machines StateGraph [11].

## PLANT MATHEMATICAL MODELING

The plant modeling has two goals: first to assure that the controller specification translates the desired system behavior and, second, to minimize the cycle time for repetitive automation systems processes. In this paper these two items are discussed: to be sure that the system behaves as expected – without leading to dangerous situations – and to maximize the productivity of the process that implies the maximization of the number of batches being processed in parallel, in tank1 and tank2. For that reason, it was developed a hybrid model with three stages for the evaporation process. Table 2 depicts the differential and algebraic equations used to model each one of the evaporator system stages.

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

TABLE 2

SYSTEM DESCRIPTION (DIFFERENTIAL AND ALGEBRAIC EQUATIONS)

In this model it was considered the pressure increase 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 due to the increase of temperature. The evolution to stage 2 happens when the alarm temperature ($T_{Alarm}$) is reached (in agreement to what is presented in Figure 2). In this stage, characterized by a temperature decrease, 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), it is obtained when the tank2 (T2) is empty, the heat loss is the only significant term of the heat balance, promoting a continuous slow decrease 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, the developed model is of hybrid nature. The main required parameters and algebraic equations are detail presented in the Table 2.

The setting of alarm temperature ($T_{Alarm}$) is chosen correctly to accomplish the two following opposed and important properties: On one hand it must be low enough to avoid dangerous temperature and pressure values, and on the other hand it has to be sufficiently high so that temperature *T* does not fall below a crystallization temperature before liquid level in tank1 ($H_1$) becomes zero.

## MODELICA MODEL OF THE SYSTEM

Due to the described potentialities, it was developed a global model of the evaporator system, already presented in the previous sections. The plant was modeled as the controller using the Dymola software and the object-oriented programming language Modelica [12-13]. Additionally, to model the controller, it was used the library for hierarchical state machines StateGraph [11], which are included in the Dymola software.

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

Figure 3 shows the global Modelica model of the system, being highlighted the two main parts, the physical part (plant) on the left, and the controller on the right.

Due to the reason that a discrete controller has been specified to control the hybrid plant, it was also necessary to implement an appropriate interface, to convert the analog output signals of the plant (tank levels, temperatures, concentrations,…) to digital signals, that can be used as inputs of the discrete controller.

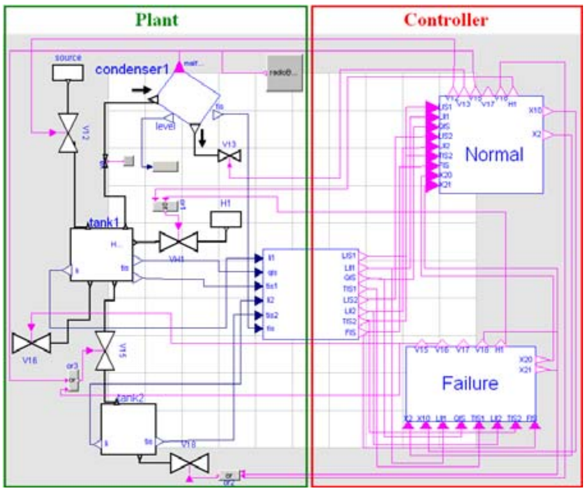
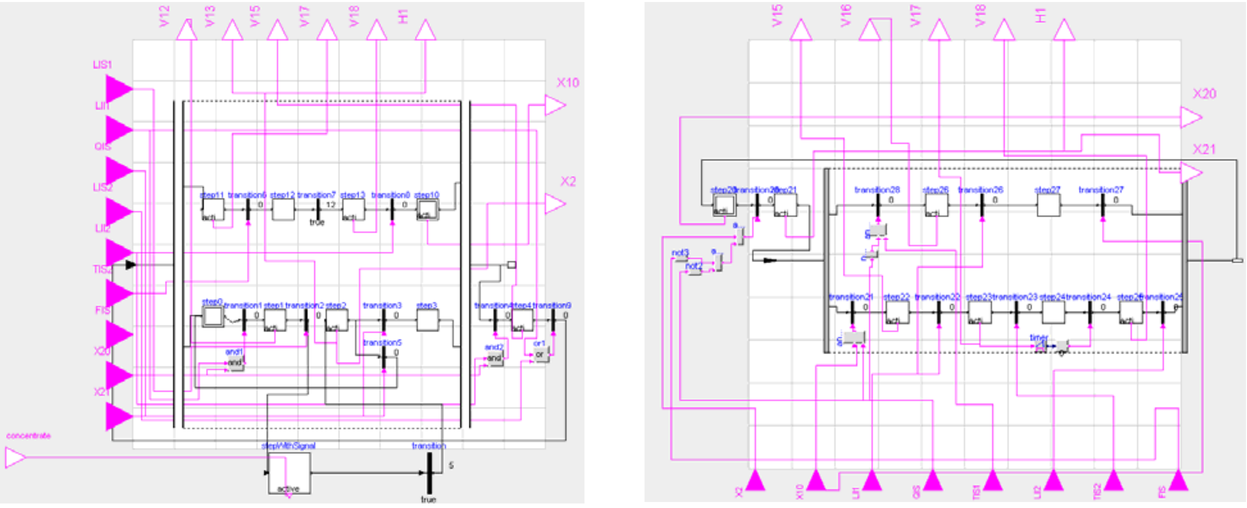


FIGURE 3
SFC GLOBAL MODELICA MODEL OF THE EVAPORATOR SYSTEM

Figure 4 shows the controller specification presented in Figure 2 translated to Modelica modeling language, using the library for hierarchical state machines StateGraph.



A) NORMAL OPERATION B) FAILURE OPERATION

FIGURE 4
MODELICA STATEGRAPH SPECIFICATION OF THE CONTROLLER – (A) NORMAL OPERATION MODE AND (B) FAILURE OPERATION MODE

## SIMULATION RESULTS

In this section, the obtained simulation results are presented and discussed, 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 implies the maximization of the number of batches being processed in parallel, in tank1 and tank2.

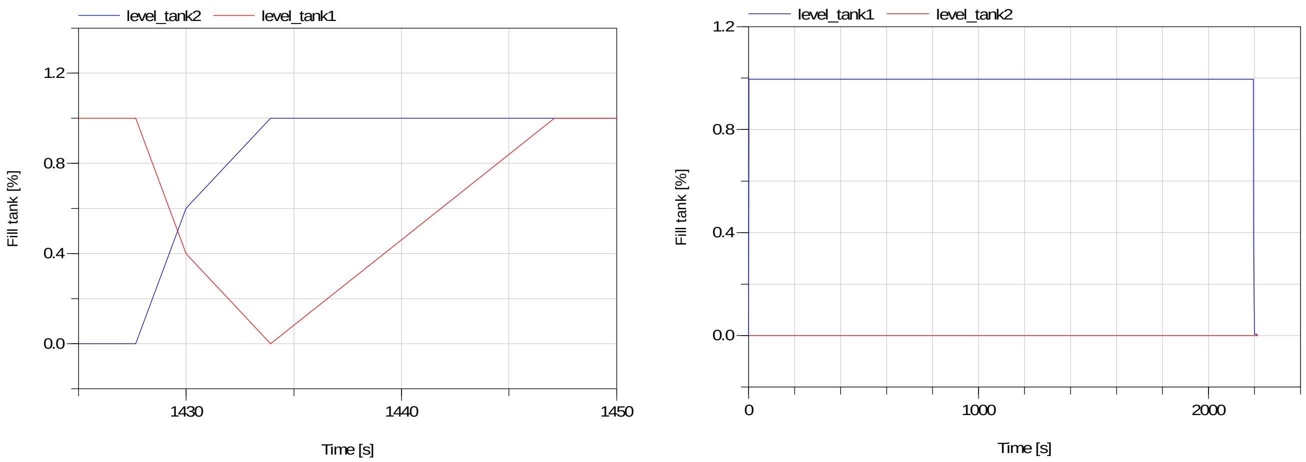
Moreover, these simulations can be seen as a “system preliminary analysis” to check if the system behaves in agreement to a given specification for a particular case. However, it must be noticed that this is not a verification in the strict sense, since it relies on the appropriate selection of the considered cases.

In order to perform the hybrid model simulation with different heating power’s, 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, and for all simulations performed, the Dass algorithm [14] with 1000 output intervals was used.

The first simulation performed was used to verify if the SFC of the controller system (see again Figure 2), modeled with Modelica language with the library for hierarchical state machines StateGraph, simulated correctly the evaporator system during its normal operation.

Figure 5 shows the results of the first two simulations, related to the normal operation and failure operation modes for the level tanks. The failure mode was a consequence of the condenser malfunction during the production cycle that caused the solution temperature in the tank1 to reach the alarm temperature set to 390 K.

Observing Figure 5A) it can be concluded that the normal operation mode is properly simulated by the developed program, since the two main properties that are important to prove are confirmed, for instance, the drainage of the solution present in the tank 1 should only happen when tank2 is empty and also the filling of tank1 is to happen soon after it is empty. On the other hand, observing Figure 5B), it can be also concluded that the failure operation mode is properly simulated, since it is proved that the tank1 is drained through the safety valve (V16 – see Figure 2), because tank2 remains empty.



A) NORMAL OPERATION

B) FAILURE OPERATION

FIGURE 5

LEVEL TANKS AS FUNCTION OF TIME – (A) NORMAL OPERATION MODE AND (B) FAILURE OPERATION MODE OF THE EVAPORATOR SYSTEM

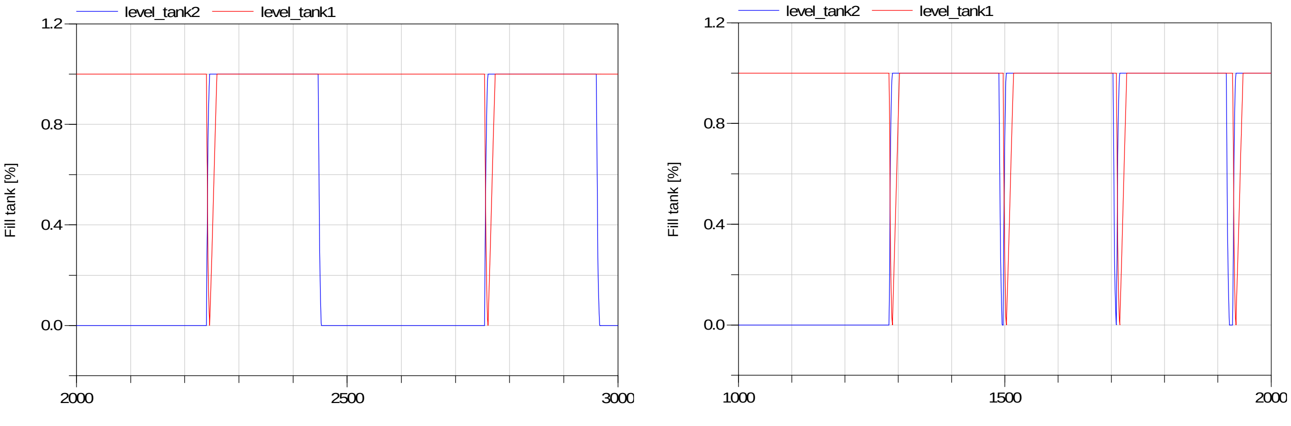
After being concluded that the normal and failure operation behavior is properly simulated by the proposed developed program, other simulations were performed to obtain the relationship between several physical process parameters that can maximize the number of batches in the evaporator system.

The optimization of the number of batches depends on the best synchronization between the time that the solution present in tank1 is prepared to be drained and the time that tank2 finishes its draining, because it decreases the loss of time in the process.

Among all the physical variables of the process (see Table 2) it was chosen the heat supply rate ($Q_{Heat}$) because it is the most relevant variable that determine the rate of the steam formation (that condenses in the condenser C) and correspondingly, the time that the solution 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 200 s for the solution powder-processing operation carry out in tank2.

Figure 6 illustrates the behavior of the model given in the Table 2, for a heat supply rate ($Q_{Heat}$) of 2500 W and 3170 W.



A) HEAT SUPPLY RATE OF 2500 W

B) HEAT SUPPLY RATE OF 3170 W

FIGURE 6
LEVEL TANKS AS FUNCTION OF TIME WITH: (A) HEAT SUPPLY RATE OF 2500 W AND (B) HEAT SUPPLY RATE OF 3170 W

Analyzing Figure 6A) it can be mentioned that a great synchronism lack happens between the time that the solution present in tank1 is prepared to be drained and the time that the tank2 finishes its draining. It can also be concluded that using a heat supply rate of 2500 W it will lead to a loss of time in the process of about 300 s.

The synchronism that occurs between the time that the solution in the tank1 is prepared to be drained and the time that tank2 finishes its draining can be confirmed observing Figure 6B).

Another excellent synchronization can also be found in the Figure 7, which presents the simulation results obtained for the time period when the transfer of the solution between tank1 and tank2 takes place, because the losses of time do not exist in the process.

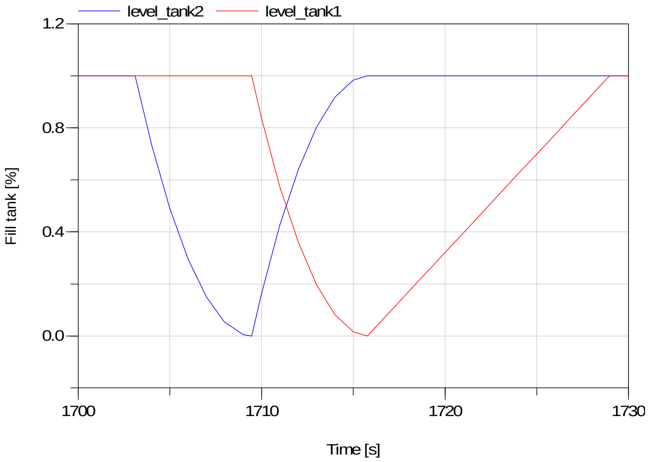


FIGURE 7
LEVEL TANKS AS FUNCTION OF TIME WITH A HEAT SUPPLY RATE OF 3170 W FOR THE SOLUTION TRANSFER TIME PERIOD BETWEEN TANK1 AND TANK2

According with the obtained simulation results, it can be concluded that the developed system controller in Modelica StateGraph specification, based on the direct application of the SFC specification, drives the system to obtain a required operation behavior. Additionally, it can be concluded that the simulation of the system control program was extremely important because it was possible to debug a set of errors in the program of the controller.

## CONCLUDING REMARKS

The simulation used to evaluate the controller and plant behavior has been developed and proposed in this paper.

The present research proved to be successful using the Modelica programming language to obtain a plant model and to use it, in a closed-loop behavior, with the controller model.

Some parameters and functional aspects of the system have been simulated in order to define a set of values of different variables that make the system dependable. Also the discussion about the critical steps to be improved – in order to obtain lower time cycles considering that the system is repetitive – was presented.

The Integration of knowledge, skills and performance relating to Competency-Based Education [15-20] in the Automation Teaching at the Mechanical Engineering Department of the University of Minho, was implemented based on case studies. The role of the teachers in this learning process was just to be coaches to support students in practice. The students were free to choose between several ways of gathering information and decide which the best way to accomplish the case study proposed.

The results of the implementation of these learning methodologies were very interesting, since the successful approbation in the final examinations was very high. This good result was obtained due to the considerable increase of the student's motivation for the approached matters.

Another important characteristic of these projects is the opportunity of increasing the promotion and motivation of new researchers in the fields of science and technology among the youth, sometimes difficult to achieve.

## ACKNOWLEDGEMENT

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