PETRI NET MODEL OF A PRODUCTION PROCESS FOR AGARICUS BISPORUS MYCELIUM

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ABSTRACT

The development of a Petri net model in food industry is the topic of this document. In particular, the production of mycelium seeds of common mushroom (Agaricus Bisporus) is addressed. This product constitutes an essential first step in the cultivation of common mushroom. The model covers all the stages in the manufacturing of mycelium, detailing shared resources, conflicts, duration of tasks, as well as the amount of stored raw materials. As a consequence, the Petri net model is appropriate for decision making support by means of simulation and what-if analysis or optimization. The model is also suitable for structural analysis. Applying this model, it may be possible to improve the knowledge of the behavior of the production facility, as well as to identify bottlenecks, deadlocks, to quantify the number of common resources required, and to find out optimal or quasi-optimal assignment of resources to the different production tasks.

Keywords: Petri nets, Agaricus Bisporus, food industry, mycelium, decision support, simulation, model.

1. INTRODUCTION

The development of accurate models of production facilities may lead to the improvement of the expected results. In fact, the model of a system can be used as a practical tool for widening the knowledge of the system itself and its behavior. Furthermore, several techniques can be applied for structural analysis and performance evaluation with the purpose of quantifying the results expected from the system under a particular configuration (Latorre et al. 2013b).

As a consequence, developing a model of a production system may be a useful step for guaranteeing its sustainability and success (Recalde et al. 2004). Regarding the objectives of the production facility described in the model, the concept of success would be defined following different approaches, such as financial, social, or environmental criteria.

In particular, food production processes experience strong competition in a world-wide market. Continuous improvement and appropriate decision making are very convenient items for the survival of the involved companies.

Many processes in food industry can be described as discrete event systems. Furthermore, Petri nets constitute a modelling formalism suitable for describing discrete event systems showing parallelism, concurrence, synchronization, and resource sharing (Silva 1993), (David and Alla 2010).

Several authors have already described Petri net models of production systems belonging to the food industry. See for example Guan et al. (2010), Latorre et al. (2015), Latorre et al. (2014), Latorre et al. (2013a), Latorre et al. (2012), Léger et al. (2011), Melberg and Davidrajuh (2009), or Shikanai et al. (2008).

Leiva et al. (2015a) addresses the analysis of the environmental impact of the *Agaricus bisporus* mycelium production, describing a production process for this product. Moreover, Leiva et al. (2015b) addresses the complete process of cultivation of the mushroom. However, as far as the authors of this document know, there is not any Petri net model of a facility for producing mycelium seeds reported in the literature.

In this paper, a Petri net model of a facility for the production of mycelium seeds of the common mushroom is described. The model that is detailed in this document has been developed as a result of a tradeoff between level of detail and size, since the computational cost of simulating a Petri net model is proportional to the its size.

Next section is devoted to the description of the production facility and the production process of mycelium seeds, while section 3 introduces briefly the modelling formalism. Section 4 details the Petri net model of the system and the following two sections focus on the conclusions and the bibliographical references respectively.

2. PRODUCTION PROCESS

In the present paper, the production process of an essential raw material for the cultivation and production of common mushroom is discussed. In particular, a Petri net model of the production process of mycelium seeds of Agaricus Bisporus is developed.

Common mushroom is one of the most successful mushroom consumed throughout the world, due to both its appreciated gastronomical and pharmacological properties.

Mycelium is the mass of hyphae and constitutes the vegetative body of a mushroom. In order for the mycelium to reproduce and form fruiting bodies, it is necessary that two compatible monokaryotic mycelia join and form a dikaryotic mycelium.

The three main stages in the mycelium production process, which are considered in the Petri net model developed in the present paper are:

a) Preparation of the growth medium for the mycelium.

At this stage, sorghum, wheat, rye seeds, or other appropriate products are selected as growth medium for the mycelium.

These products are processed for improving the growth performance of mycelium.

b) Creation of the inoculum.

A first phase of this stage starts with the cultivation of the mycelium in Petri dishes, under artificial culture medium in a lab.

c) Preparation of the mycelium seed packages.

The mushroom mycelium, inoculated in grains, is incubated at an optimal temperature. When the incubation finishes, the seeds are kept at low temperature and mixed with a compost preparation to produce seed packages in the culture.

3. MODELLING FORMALISM

Petri nets constitute a modeling paradigm particularly gifted for describing discrete event systems showing a complex behavior, such as parallelism, concurrence, synchronization, or competition for shared resources.

Following Silva (1993) it is possible to define a Petri net in the following way:

Definition 1. A marked Petri net or net system R is a couple $\langle N, M_0 \rangle$, where

i) N is a Petri net, i.e. a four tuple $\langle P, T, Pre, Post \rangle$, such that P and T are disjoint and finite sets of places and transitions respectively, $Pre: P \ge T \rightarrow N$, and $Post: P \ge T \rightarrow N$.

ii) M_0 is an initial marking, i.e. an application of P on the set **N** of non-negative integers.

The model to be presented in this paper is timed. This means that the duration of some production tasks are integrated in the model of the system. In particular it will be considered a T-timed Petri net, where time will be added to the transitions of the Petri net model.

According to David and Alla (2010), it is possible to state the following definition:

Definition 2. A T-timed Petri net is a pair $\langle R$, Tempo> such that:

R is a marked Petri net;

Time is a function from the set *T* of transitions to the set of positive or zero rational numbers. Tempo $(T_j) = d_j =$ timing associated with T_j .

The evolution rules of a Petri net is modified, when introducing time. In the case of a T-timed Petri net, an enabled transition T_j does not become necessarily firable, since an additional necessary condition implies that a time Tempo(T_j) = d_j should elapse after enabling. Two additional items are worth to be mentioned at this point. There may be transitions with a 0 time associated, called immediate transitions. For example, if T_k is an immediate transition, then Tempo(T_k) = d_k = 0, meaning that, when enabled, it becomes also firable. Furthermore, a conflict may lead to indeterminism in the firing of the transitions involved, since the firing of some of them implies the disabling of the others.

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In this document immediate transitions are represented by thin bars, while timed transitions (delay time greater than zero) are drawn by means of rectangles.

4. DEVELOPMENT OF THE MODEL

The model of the production facility has been developed following a bottom-up approach. This methodology consists in developing a detailed model of every subsystem and linking them by means of certain places or transitions.

The main subsystems of the production system are three:

- a) Facility for the preparation of the growth medium of the mycelium.
 This stage of the production process consists of the preparation of the bags of rye, sorghum, or wheat, which will be inoculated by the mycelium.
 The model for this subsystem has been represented in Figure 1.
- b) Facility for the creation of the mother culture and mother spawn.

This stage is focused on the creation of the culture medium for the mycelium and its inoculation in the growth medium developed in the previous subsystem.

The model for this subsystem is represented in Figure 2.

c) Facility for the creation of the final spawn or mycelium seed packages.

In this stage of the production process, the mycelium is inoculated in the growth medium and is left to sprout until the mycelium has completely colonized it. The resulting product is packaged and stored until its expedition to the customers, which use to be composters creating compost from the seed packages.

The model for this subsystem, in conjunction with the previous one, has been depicted in Figure 2.

4.1. Subsystem 1: preparation of the growth medium

The model of this facility, see Figure 1, consists of 39 places and 28 transitions. Some of the transitions are timed, represented by rectangles and the rest of them are immediate transitions, depicted by thin bars.



Figure 1. Model of the facility for the preparation of the growth medium of the mycelium.

This model has been depicted in two columns that represent two sequential stages in the production process.

The first step represents the raw materials supply, followed by the stage of mixing and boiling the raw materials. Next, the operation of disinfection begins, to remove pathogen microorganisms, which might reduce drastically the efficiency of the production process.

The following stage is the cooling process, followed by the filling of plastic bags with the growth medium.

The last steps are a sterilization phase in autoclaves, another cooling process and the transport to the inoculating area, which leads to a place labelled "Bags with grow medium", which is a link place to the model represented in Figure 2. In fact, this same place has also been drawn in the model representing the creation of the mycelium seed packages.

Analogously, there are another three places that are shared by both models. One of them is labelled "Carts", and represent the transportation means used in most of the conveying tasks of materials in the production process. This resource is used in this subsystem and released in subsystem 3, after the storage of the final product. Another shared place is labelled "operator" and represents a shared resource, the operators, who can devote their time to different tasks. The last shared place is labelled "plastic bags" and represents the bags used to contain the growth medium for the mycelium.

This model presents several freedom degrees, which can be implemented as fixed numbers, stochastic values, or controllable parameters, also called decision variables, depending on the conditions of the real facility that has been modelled.

Some of these freedom degrees are represented by means of the initial marking of certain places. Others are associated to the conflicts that arise in the evolution of the Petri net model. It has not been included in this model, but it is even possible to introduce structural parameters, as the weight of certain arcs, to represent, for example, the size of the conveying lot of product or raw materials at certain stages of the process. The freedom degrees associated to the initial marking of certain places have been classified into two categories:

- a) Raw materials, represented by the letter "m" inside the places.
- b) Shared resources, represented by the letter "r" inside the places.

The main difference between the elements of both categories is that raw materials are consumed and resources are used and released for additional uses. The subsequent wear of the resources, as a consequence of their reiterated usage, has not been considered in this model, but it may be added easily.

The list of raw materials in this system 1 is the following:

m₁: water

m₂: calcium carbonate

m₃: rye, wheat or sorghum

m₄: chalk

All these first four raw materials are direct components of the growth medium for the mycelium.

m₅: disinfectant for disinfecting the growth medium

m₆: plastic bags for sealing inside the growth medium, prior to the sterilization and cooling processes.

Moreover, the list of shared resources in this same subsystem are:

 \mathbf{r}_1 : large vats for mixing and boiling the raw materials

 \mathbf{r}_2 : carts for conveying the semifinished and finished products

 \mathbf{r}_3 : operator developing any general task in the production process

 \mathbf{r}_4 : size in kg of the vat in the filling and sealing machine for the production of growth medium bags

 \mathbf{r}_5 : autoclaves for the sterilization of the growth medium bags.

Other parameters of the model for this first subsystem are the delay times associated to the timed transitions: d_1 to d_{14} .

Many of these timed transitions are related to conveying operations, such as d_1 , d_2 , d_3 , d_{10} , d_{12} , and d_{14}

Other timed transitions are related to production operations, such as mixing, boiling, disinfecting, cooling, filling, sealing, or sterilization in autoclaves.

Additional freedom degrees are the conflicts of the net, i.e. the places with more than one output arc to transitions with the same associated delay, when the marking of the place is not able to fire all the output transitions simultaneously. In this case there is a conflict in the place "Operator".

This conflict is associated to the need of defining a managing strategy for the assignment of the available operators to the different tasks that may arise along the production cycle.

There is a structural conflict in the place "Water" but if there is not any shortage in the water supply, it is not expected that this structural conflict becomes an actual conflict. In other words, if there is enough water, it is not necessary to choose in which production operation should be used. All the operations can receive all the water they request. Finally, it might be possible to add structural parameters in the Petri net model of this subsystem as freedom degrees, defining, for example, the lot size in certain transport operations or in the processing tasks of certain machines. These lot sizes would be limited by the capacity of the carts or machines. However, simulating the results under different capacities for the industrial equipment, some conclusions could be raised on the decisions to acquire and install these elements.

4.2. Subsystems 2 and 3: preparation of the mycelium seed packages

The model of these two subsystems has been represented in Figure 2 and is composed of 47 places and 35 transitions.

The different steps of the production process are performed in different stages of the facility, represented sequentially in the Petri net model, depicted in two columns. The first step is the creation of the culture medium for the mother culture and it is performed in the lab, by specialized technicians. This step os followed by a sterilization of this medium and the inoculation of the mycelium. This mycelium grows in Petri dishes and later on in rye bags, starting a first stage in sprouting chambers. The obtained mycelium is inoculated again twice in rye bags, followed by growth in sprouting chambers to maximize the production results and a final storage precedes the expedition to the customer. A final place labelled "sold" inventory the mycelium seed packages sold to the customers.

These subsystems present several freedom degrees, which constitute one of the interesting potential of the model presented in this paper. These freedom degrees allow the application of different methodologies, such as what-if analysis or optimization to check different configurations of the model that lead to the best achievement of the objectives of the company exploiting the production facility.

The freedom degrees belong to the following categories:

- 1) Initial marking:
 - a. Raw materials $(\mathbf{m}_5 \text{ to } \mathbf{m}_{10})$
 - b. Resources $(\mathbf{r}_2, \mathbf{r}_3, \text{ and } \mathbf{r}_7 \text{ to } \mathbf{r}_{10})$
- 2) Delay associated to timed transitions (d_{15} to d_{34})
- 3) Actual conflicts

More in detail, the raw materials not detailed in the previous section are the following:

m₇: malt extract

 m_8 : Glucose and agar. They are in fact two different raw materials and could be represented by independent parameters associated to different places.

m₉: Peptone

The previous raw materials are the basis for the culture medium for the mother culture, which is completed with m_{10} .

m₁₀: mycelium

Analogously, the resources not explained in the previous section are the following ones:

 \mathbf{r}_6 : technician for laboratory operations

r₇: Petri dishes for the mother culture

r₈: plastic containers for a culture first sprouting stage.

 \mathbf{r}_9 : size of the sprouting chambers, measured in carts filled with product

 \mathbf{r}_{10} : inoculating machines

The delays associated to timed transitions can be controllable parameters or not, depending on the possibility for them to change as a result of a decision. For example, if it is possible to change the layout of the production system, modifying the time required for certain transport operations, the associated parameter d_i can be considered a controllable parameter.

Many time delays are associated to transport operations, such as d_{20} , d_{22} , d_{24} , d_{26} , d_{28} , d_{30} , and d_{32} .

Other delays associated to timed transitions are associated to operations, such as mixing the raw materials, disinfecting the culture medium, inoculating the mycelium, growing and sprouting, filling and sealing, as well as the last operations of storage and expedition.



Figure 2. Model of the facility for the preparation of the mycelium seed packages.

Finally, the freedom degrees associated to conflicts of the Petri nets are the following ones:

- a) Place labeled "Lab technician". The actual conflict requires dealing with the priorities of the output transitions, in order to determine the optimal sequence of mixing the raw materials to elaborate the culture medium.
- b) Place labeled "Operator". Already mentioned in the previous section.
- c) Place labeled "Bags with growth medium". This place is a link place with the model of subsystem 1. If there are enough bags for all the requests there will not be any actual conflict. Otherwise, it will be convenient to decide the best strategy for assigning this resource to the different production operations.
- d) Place labeled "Size of sprouting chambers". If there is enough place in the sprouting chambers for all the production needs, there will not be any actual conflict. Otherwise, it is necessary to find the optimal assignment of this resource to the production requests.
- e) Place labeled "Inoculating machine". Similar to the previous ones.

5. CONCLUSIONS

A model of a production facility of mycelium seed packages of Agaricus bisporus has been presented in this document. A T-timed Petri net has been chosen as modeling formalism to represent the facility (seen as a discrete event system) due to its suitability to naturally describe the particularities of such a facility. As a result, a Petri net model with 82 places and 63 transitions is described and depicted in detail in two figures. This model explicitly includes a quantitative representation of different freedom degrees of the facility. Each one of them can be specified as fixed numbers, controllable parameters, or stochastic values, depending on the real facility in a particular application. This model contains 20 parameters in the initial marking of the net, representing amounts of raw materials and resources, 34 parameters in the delay associated to a same number of timed transitions, and 5 structural conflicts. All the freedom degrees require a particular configuration for operating the production facility and the model allows testing different configurations and simulating the evolution of the system to quantify the performance of every solution. Furthermore, the model itself can be used to improve the knowledge of the real system, performing structural analysis, and identifying bottlenecks and deadlocks; thus, being a practical tool for decision making support.

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