Hybrid Petri Nets to Re-design Low-Automated Production Processes: the Case Study of a Sardinian Bakery

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Abstract: This paper shows the practical relevance of first-order hybrid Petri nets in the re-design process of low-automated production systems. In particular, we analyze the case study of a bakery producing "pane Carasau", a typical Sardinian bread, whose traditional production plant currently has difficulties in coping with the constant increase in market demand. Through first-order hybrid Petri nets, the current functioning and the operating features and dynamics of the case study are modelled, waste sources and bottlenecks are detected, and alternative re-designed scenarios are implemented and evaluated to identify the most suitable reengineering actions to be developed.

Keywords: First-Order Hybrid Petri nets, Reengineering, Re-design, Production processes.

1 INTRODUCTION

"Pane Carasau" is a typical round-shaped and thick bread produced in Sardinia (Italy). It is particularly appreciated for its long-life duration, which is due to the low percentage of humidity (Pagani *et al.*, 2014). In recent years, while the demand for "pane Carasau" has constantly increased, the organization of production in traditional plants has lagged behind. This is mainly due to the small size of bakeries, the difficulty of transforming a traditional production process into a (semi)-industrial one, and the problems induced by implementing new technologies (Paschino *et al.*, 2007). As a matter of fact, although some levels of automation have been reached, in most production sites significant parts of the production process are still manual or use small and often inefficient machines that greatly impact on the labour time, increasing it on average by 50% (Paschino *et al.*, 2007). These inefficiencies have encouraged research on experimental methods to increase the overall levels of automation and improve different aspects of this production process. As a result, traditional bakeries have to rationalise their plants, and the machines in use are to be improved to satisfy the market needs (Paschino *et al.*, 2007). On such bases, it appears evident the importance of conducting proper preliminary cost-benefit analysis, before proceeding in any type of investment. For this purpose, simulations and numerical analysis can be effectively used to evaluate possible solutions and to identify the most effective ones.

In this paper we show how First-Order Hybrid Petri Nets (FOHPNs) can be used in the context of low-automated bakeries to suitably represent and simulate the process flows, detect possible sources of waste, bottlenecks, or inefficiencies in the current configuration, evaluate the available improvements that can be obtained in the re-designed production process, perform what-if evaluations and cost-benefit analysis, and control the system behaviour. Therefore, by such a re-design process, managers are supported in the resource planning, in the job scheduling, and in the evaluation of the system throughputs and of the production process capacity.

2 STATE OF THE ART

The re-design of production processes can ensure competitiveness and enable companies to be more adaptive to changes in the market dynamics. To this aim, several approaches have been proposed in the literature, among which, due to the intrinsically discrete nature of such systems where demand and resource utilization are guided by discrete events, Discrete Event System (DES) models are largely appreciated (Choi and Reveliotis, 2003; Campos *et al.,* 2014). Indeed, as extensively proved in the literature, DESs allow to model, analyze, and re-design systems to meet certain requirements, improve their efficiency and flexibility, and optimize their performance (Krenczyk *et al.*, 2016). A recent review of DES models for the design, optimization, and management of production systems is in Negahban and Smith (2014).

In the context of DES models for production process re-design, Petri Nets (PNs) are one of the most common formalism. They allow a graphical representation of DESs, which is a detailed and realistic view of the characteristics, hierarchies, and dynamics of production systems; they are suited for implementation by computer languages; they can systematically represent all the system activities, including concurrency, synchronization and resource sharing at various levels of detail; they allow performance evaluation, analysis, and control of production systems thanks to their easily

readable aspect, structure, scalability, and modularity; they can support decision making through the assessment of what-if scenarios; they can be used to analyze problems occurring in business processes; they make strategies/policies more understandable even to non-expert users; they are suitable to represent and simulate the process both before and after reengineering (Basile *et al.*, 2007; Dotoli *et al.*, 2014; Dotoli *et al.*, 2016, Cavone *et al.*, 2016). In fact, PNs are more suitable than other methods to model and simulate modern production systems (Long *et al.*, 2015). A review on the use of PNs in this field is provided by Pawlewski (2010). A large variety of PNs extensions have been developed (see David and Alla, 2010; Silva and Recalde, 2004), among which First-Order Hybrid Petri Nets (FOHPNs) are particularly suitable to model and control manufacturing systems. FOHPN models allow to explicitly and simultaneously represent time-driven and discrete event dynamics and, thanks to the continuous features of system design parameters, they allow to solve integer linear programming problems to optimize in a closed-loop fashion suitable operational parameters that can improve the performance of the system (Balduzzi *et al.*, 2000). In the relevant literature, PNs, and FOHPNs in particular, are extensively adopted to model, analyze, and control highly automated manufacturing systems (Hu and Zhou, 2015). On the contrary, FOHPNs are seldom utilized for modelling and optimizing low-automated business processes (such as traditional bakeries). In this paper we show how FOHPNs can be effectively used also to reengineer low automated production processes.

3 THE CONSIDERED CASE STUDY

In this section we first introduce the considered case study. Then we show how such a production process can be modeled using FOHPNs. Finally, we discuss some possible strategies to improve the business efficiency.

3.1 The Production Process of "Pane Carasau"

The production of "Pane Carasau", the most important product of "Vecchio Forno" bakery (www.ilvecchioforno.it) is sequential and involves a series of machines and manual processing stations connected through conveyor belts. The whole process can be sketched as follows (see Fig. 1):

1) ingredients (i.e., water, yeast, durum wheat, and salt) are mixed in a kneading machine for about 20 minutes;
2) the dough has an initial fermentation (at 28-32°C for about 30 minutes) in the leavening machine;

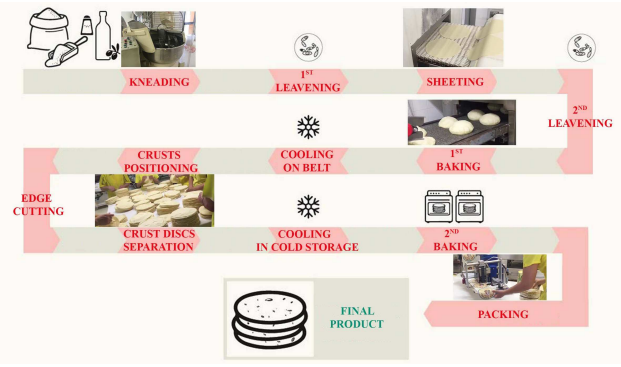


Fig. 1. The logical scheme of the current production process.

3) the dough is sheeted and cut in disks of 18 cm in diameter;
4) disks are put in a secondary leavening machine (for about 40 minutes at 32°C);
5) disks are baked at about 560-580°C for a few seconds. Due to the flash evaporation of water, each round sheet swells and loses about 2% of its weight;
6) disks are cooled on a belt for 5-6 minutes, thus deflating;
7) disks are manually positioned on a working desk to check for creases or deformations;
8) disks are stacked in groups of 5-6 crusts and cut along their edges by a cutting machine (note that at this stage scraps, being already cooked, are discarded, with a loss of about 15% of product);
9) puff pastries are manually separated by dividing the top from the bottom to obtain two symmetrical sheets;
10) sheets are cooled for about 1 hour at 4°C in a cold storage;
11) sheets are baked and toasted for 15-20 seconds at 400°C (in a single or in a double oven);
12) sheets are weighted, packed in groups of 0.5 kg each, and labelled for distribution and sale.

3.2 The FOHPN of the As-Is Production Process

For the sake of brevity, we omit here the detailed description of FOHPNs basics (see Balduzzi *et al.* (2000) for details). We only recall that a FOHPN is a structure $N=(P,T,Pre,Post,D,C)$, where P is the union of a set P_c of continuous places depicted as double circles and denoted by $p_{c,i}$ (i=1, …,m_c) and a set P_d of discrete places depicted as circles and denoted by $p_{d,i}$ (i=1, …,m_d); similarly T is the union of a set T_c of continuous transitions depicted as double boxes and denoted by $t_{c,i}$ (i=1, …,n_c) and a set T_d of discrete transitions denoted by $t_{d,i}$ (i=1, …,n_d). Set T_d is further partitioned into immediate transitions T_I (depicted as bars), deterministic timed transitions T_D (depicted as black boxes), and exponentially distributed timed transitions T_E (depicted as white boxes). A marking M is a function that assigns to each discrete place a non-negative number of tokens (represented by black dots) and to each continuous place a fluid volume. The marking of place p is denoted as $M(p)$.

The FOHPN model of the process described in the above sub-section is shown in Fig. 2, where each working phase is highlighted through a dashed rectangle. Table 1 illustrates the notation and describes the physical meaning of the places in Fig. 2. Table 2 summarizes the physical meaning of continuous transitions and the interval $[mfs,MFS]$ (minimum and maximum firing speed) in which their Instantaneous Firing Speeds (IFSs) can vary. The interval has been determined by statistical evaluations on six months of activity data. Finally, Table 3 summarizes the physical meaning of discrete transitions, including their characteristic parameters (i.e., the time delay d for deterministic transitions and the average value λ for exponential ones). In the current configuration the following arc weights are considered: $Pre(p_{c,7},t_{d,6})=X=50$, $Pre(p_{c,9},t_{d,7})=Y=20$, $Pre(p_{c,11},t_{d,8})=Z=60$, and $Pre(p_{c,18},t_{d,11})=K=119$, which represent the quantity (in kg) of product flowing in the different phases of the process, and will be subject to changes in the re-design scenarios.

Analyzing Fig. 2 it may be noticed that each phase of the production process is characterized by a logical controller that checks the product weight in each workstation. For instance, looking at Fig. 2, the kneading phase contains a logical control structure, constituted by places $p_{c,3}$, $p_{d,5}$ and transition $t_{d,2}$, which ensures the passage of the dough from the kneader to the leavening machine only after producing a quantity of product equal to 143 kg. The same happens in the remaining phases, since each workstation must process a specific amount of product before making it available for the subsequent phase. Note that the model of the dough sheeting machine includes a fault and restore cycle, represented by the discrete places $p_{d,7}$, $p_{d,8}$, and the discrete transitions $t_{d,4}$, $t_{d,5}$. Clearly, similar cycles may also be modelled for the other phases. However, as a first approximation, we only consider the fault/restore cycle of the sheeting machine since it is the most frequently affected by malfunctions.

The described FOHPN model is first validated performing a statistical analysis of the outcomes of the model with respect to the historical data collected in the bakery over 6 months of activity (see Cavone *et al.* (2016) for details on the validation procedure) and is then used to simulate and analyze the system behaviour in the nominal operating conditions and detect possible inefficiencies and/or bottlenecks in the process. We remark that, in the nominal operating conditions, the IFS associated with continuous transitions are randomly chosen in the corresponding speed interval. On the contrary, in the re-design scenarios, thanks to the control capabilities of the FOHPNs formalism, the IFSs are assigned so as to optimize the performance of the process.

Figure 3 shows the marking evolution of the continuous places in each workstation (except for the logic controllers) and that of the discrete place $p_{d,18}$ (final product) in the FOHPN model in Fig. 2. In particular, referring to the cutting workstation, Fig. 3 reports the evolution of marking $M(p_{c,17})$, which shows that the maximum quantity of scraps is about 21 kg (on 143 kg of the initial dough). Looking at Fig. 3 it is evident that, as imposed by the logic controller rules, each phase only starts when the required weight of product is achieved., e.g., $M(p_{c,4})$ (1st leavening phase) starts increasing only after $M(p_{c,2})$ (kneading phase) has reached its maximum value. Moreover, the evolution of $M(p_{d,18})$ (packing phase) shows that the process is completed in 307.5 min., i.e., in about 5 hours.

3.3 The FOHPN of the Re-designed Production Process

Currently, the "Vecchio Forno" bakery is managed through knowledge-based decisions. The personnel organizes and optimizes the production process and the use of resources without standard procedures or decision support systems. Since the bakery is small-sized, the machines in use cause great discontinuities in the process. In addition, some phases are manually performed by dedicated workers. These aspects seriously affect efficiency and reliability. Therefore, the mechanization of the process would allow the bakery to increase its productivity by joining the quality of traditional products with the advantages of semi-industrial plants. Introducing processing systems, which can incorporate different phases of production, would result in an actual rationalization of working capacity, productivity, and electricity consumption. When simulating the As-Is FOHPN model the main bottleneck of the process revealed to be the leavening and baking phases, whose duration is fixed and as such do not allow to considerably reduce the duration of the production process. Hereafter, we present two particularly effective re-design alternatives (Scenario1 and Scenario2) both including an online control on continuous transitions t_c aiming at optimizing the process speed. This consists in maximizing at each macro-period (i.e., the interval between two macro-events) the objective function $J=\boldsymbol{a}^T \cdot \boldsymbol{v}$ with respect to the admissible IFSs constraint set, being $\boldsymbol{v}$ the IFS vector and $\boldsymbol{a}$ a unitary weight vector (see Balduzzi *et. al.* (2000)).

Scenario1 considers an investment in a new machine that simultaneously cuts edges and separates disks. The adoption of such particular machine guarantees a twofold advantage. On the one hand it produces a lower percentage of scraps, with respect to the current cutting machine; on the other hand it speeds up the separation of disks and decreases the incidence of manual errors. Scenario1 is obtained by properly modifying the FOHPN model in Fig. 2 as shown in Fig. 4. In particular, in Fig. 4 $Post(p_{c,16}, t_{c,8})$ drops from 0.85 to 0.95, consequently $Post(p_{c,17}, t_{c,8})$ drops from 0.15 to 0.05, and K drops from 119 to 133 kg. Moreover, in Scenario1 the transition representing the new machine, i.e., $t_{c,8}$, is characterized by a MFS=4 kg/min, instead of 1 kg/min.

Scenario2 aims at streamlining the process, speeding up the production and guaranteeing a more homogeneous product flow than in the As-Is case. The re-design mainly involves the sheeting, 2nd leavening, and 1st baking phases, i.e., the most critical phases of the process. It consists in reducing the amount of product required by the respective logical controllers to enable the subsequent phase. Referring to Fig. 2, the following weights are assumed: X=10, Y=10, Z=10. The same re-design is also adopted for the crust discs separation and cooling in cold storage phases, where the arc weight K is halved and set equal to 59.5 kg to reduce discontinuities in the flow. Note that such weight values are the minimum ones to avoid the deadlock of the process.

To properly compare the advantages arising from the two possible re-design actions, we evaluate the following indices (see Table 4): the cost of the investment [€]; the monthly cost saving [€/month]; the time required to produce 1 kg of bread [min/kg]; the percentage of scraps in the process [%]. Comparing the second and third rows of Table 4 it is to be noticed that in Scenario1, thanks to the cost saving (mainly due to the reduction in the number of workers for the separation of sheets) and to the increased efficiency of the new machine the return on investment is about 7 months. In fact, $M_{Sc1}(p_{c,14})$ in Fig. 5 differs from $M_{AsIs}(p_{c,14})$ showing that the amount of disks to be stacked on the cutting machine becomes rapidly equal to zero, since the edge cutting is faster. Similarly, $M_{Sc1}(p_{c,16})$ in Fig. 5 is modified with respect to the corresponding $M_{AsIs}(p_{c,18})$ highlighting that the cutting and separation phases are more rapidly performed. The same conclusion arise by comparing $M_{Sc1}(p_{c,18})$ with $M_{AsIs}(p_{c,19})$ (the beginning of the baking phase).

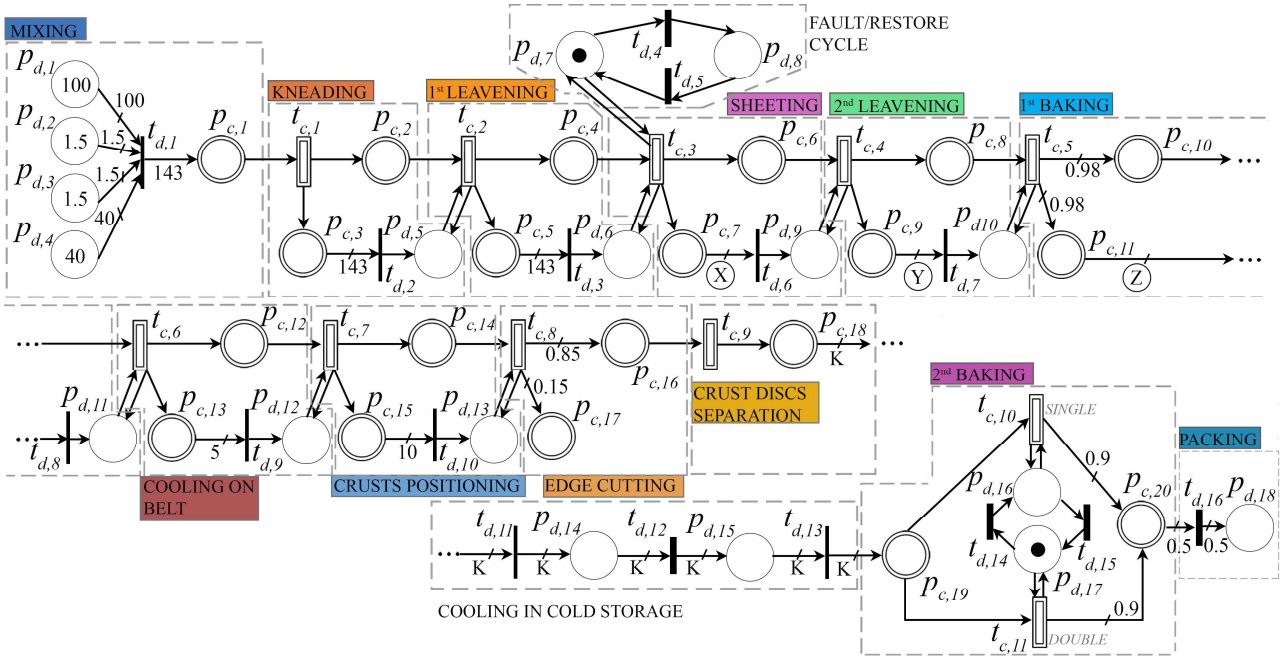


Fig. 2. The FOHPN model of the production process in Fig. 1.

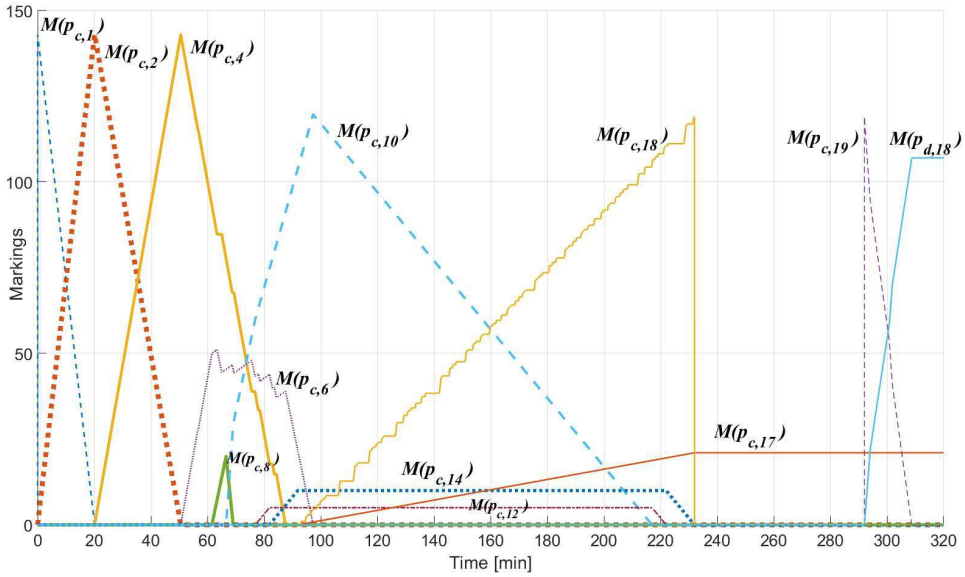


Fig. 3. Evolution of markings in the As-Is scenario in Fig. 2.

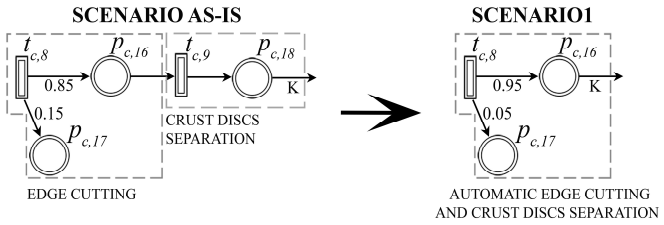


Fig. 4. Modification of the FOHPN of Fig.2 in Scenario1.

Moreover a 13% of reduction in production time (from 2.58 to 2.24 min/kg) is observed, as confirmed by comparing $M_{Sc1}(p_{d,18})$ with $M_{AsIs}(p_{d,18})$ (the conclusion of the packing phase) in Fig. 5. Finally, a 66% of reduction in the scraps production (from 15% to 5%) is observed (see the modification of $M(p_{c,17})$ in Fig. 5). On the contrary, with respect to the As-Is configuration, in Scenario2 no investment is required. As it emerges from the fourth row of Table 4, about 10% of reduction in the production time is achieved (from 2.58 to 2.32 min/kg) thanks to the new values of *X*, *Y*, *Z*, *K*, i.e., the quantity of product flowing in the process. Indeed, Fig. 6 shows that the maximum value of $M_{Sc2}(p_{d,18})$ compared to that of $M_{AsIs}(p_{d,18})$ is achieved at minute 276 instead of 307. Finally, Table 4 shows that the percentage of scrubs remains unchanged; indeed in Fig. 6 the maximum of $M_{Sc2}(p_{c,17})$ is equal to that of $M_{AsIs}(p_{c,17})$. Moreover, halving *K* allows to anticipate the cooling phase (see $M_{Sc2}(p_{c,18})$ with respect to $M_{AsIs}(p_{c,18})$) and the 2nd baking phase (see $M(p_{c,19})$ and $M_{AsIs}(p_{c,19})$), which confirms the expected reduction of the production time. All simulations are performed using a MATLAB toolbox, called HYPENS (Sessego *et al.*, 2008) on a PC with an Intel Core 2 Duo-2.80 GHz processor and 4 Gb RAM. The computation time of each replication is only few seconds.

Table 1. Physical meaning of places in Fig. 2.

Place	*Description*
p_{d1}, p_{d2}, p_{d3}, p_{d4}	ingredients
$p_{c,1}$	mix of ingredients
$p_{c,2}$	dough to be leavened
$p_{c,4}$	dough leavened
$p_{c,6}$	disks sheeted
$p_{c,8}$	disks leavened
$p_{c,10}$	disks baked
$p_{c,12}$	crusts cooled (I)
$p_{c,14}$	crusts stretched
$p_{c,16}$	crusts stacked and cut
$p_{c,17}$	scraps
$p_{c,18}$	crusts separated
$p_{d,14}$, $p_{d,15}$	crusts cooled (II)
$p_{c,19}$	crusts to be baked and toasted
$p_{c,20}$	crusts baked and toasted
$p_{d,18}$	final product
$p_{c,3}$, $p_{c,5}$, $p_{c,7}$, $p_{c,9}$, $p_{c,11}$, $p_{c,13}$, $p_{c,15}$	product weight check
$p_{d,5}$, $p_{d,6}$, $p_{d,9}$, $p_{d,10}$, $p_{d,11}$, $p_{d,12}$, $p_{d,13}$	max weight achieved
$p_{d,7}$, $p_{d,8}$	sheeting machine (fault/restore)
$p_{d,16}$, $p_{d,17}$	single/double oven availability
** Note that the colors of highlighted cells refer to markings in Figs 5-6*	

Table 2. Physical meaning and firing speed intervals of continuous transitions in Fig. 2.

Transition	*Description*	*Firing speed [mfs-MFS] (kg/sec)*
$t_{c,1}$	kneading	[0-7.15]
$t_{c,2}$	1st leavening	[3.57-4.76]
$t_{c,3}$	dough sheeting	[4.2-4.6]
$t_{c,4}$	2nd leavening	[3.57-4.08]
$t_{c,5}$	1st baking	[8.56-12]
$t_{c,6}$	cooling on belt	[0.83-1]
$t_{c,7}$	manual stretching of crusts	[0.8-1]
$t_{c,8}$	cutting	[0.8-1]
$t_{c,9}$	manual separation of disks	[5.72-7.15]
$t_{c,10}$	2nd baking (single oven)	[4.28-6]
$t_{c,11}$	2nd baking (double oven)	[8.56-12]

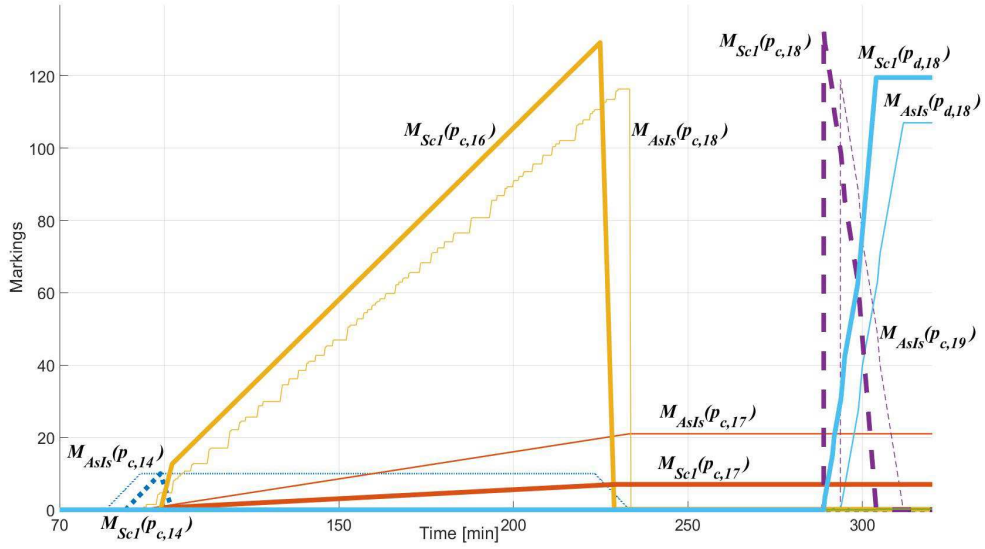


Fig. 5. Evolution of the most significant markings (Scenario1 wrt As-Is).

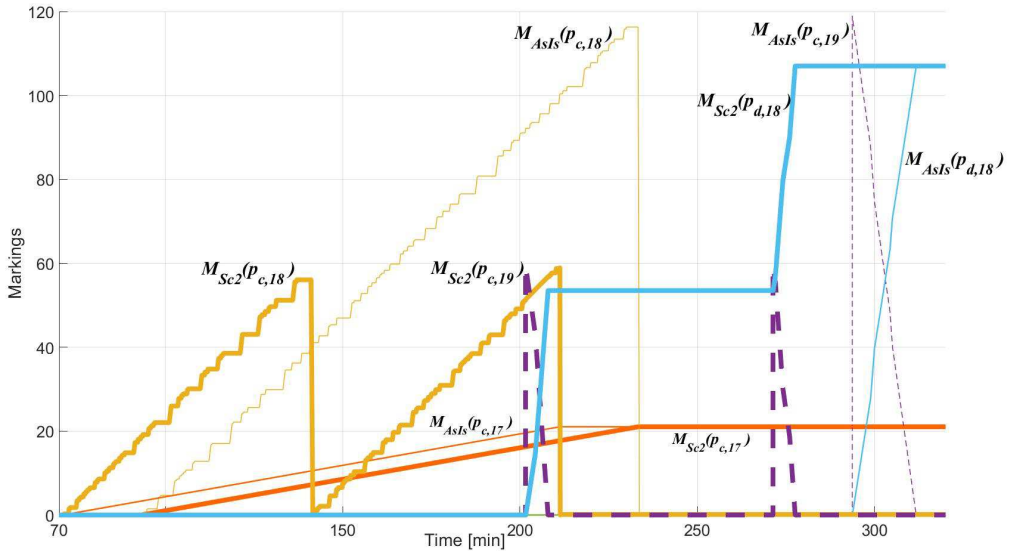


Fig. 6. Evolution of the most significant markings (Scenario2 wrt As-Is).

Table 3. Physical meaning and characteristic parameters of discrete transitions in Fig. 2.

Transition	*Type*	*Parameter*
$t_{d,1}$, $t_{d,2}$, $t_{d,3}$	deterministic, instantaneous	d=0
$t_{d,4}$	Stochastic	λ=1
$t_{d,5}$	Stochastic	λ=4
$t_{d,6}$ $t_{d,7}$, $t_{d,8}$, $t_{d,9}$, $t_{d,10}$, $t_{d,11}$	deterministic, instantaneous	d=0
$t_{d,12}$	deterministic, delayed	d=60 min
$t_{d,13}$	deterministic, instantaneous	d=0
$t_{d,14}$	Stochastic	λ=3
$t_{d,15}$	Stochastic	λ=3.5
$t_{d,16}$	deterministic, instantaneous	d=0

Table 4. Comparison of re-design and As-Is scenarios.

Scenario	*Cost [k€]*	*Saving [k€/month]*	*Prod. Time [min/kg]*	*Scraps [%]*
As-Is	0	0	307.5/119=2.58	15
Scenario1	50	7.2	298.5/133=2.24	5
Scenario2	0	0	276/119=2.32	15

From the above analysis we can conclude that FOHPNs represent a useful tool for the correct management and re-design of low-automated companies. In particular, they allow decision makers to model the process behaviour to analyze performance in the current operating conditions and identify bottlenecks and waste sources, as well as perform what-if analysis and cost-benefit evaluations in order to easily compare the possible resolution actions to be implemented. We conclude this section highlighting that the FOHPN model could also allow to easily handle unusual and unpredictable events that might occur during the system operations. Indeed, thanks to the low simulation times, a new analysis under different functioning conditions may easily be performed.

4 CONCLUSIONS AND FUTURE WORKS

In this paper we have shown how FOHPNs can be efficiently used to improve the production process of low-automated companies. We considered the case study of a small-sized and low automated bakery producing "Pane Carasau". We modelled the bakery and its current functioning, detected the waste sources and bottlenecks, and identified and evaluated in terms of cost-benefit two re-designed production scenarios.

Future work will consider the investigation of multi-criteria decision-making techniques to rapidly identify the most effective re-design action, and investigate the interactions of the different production lines and further improvements.

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