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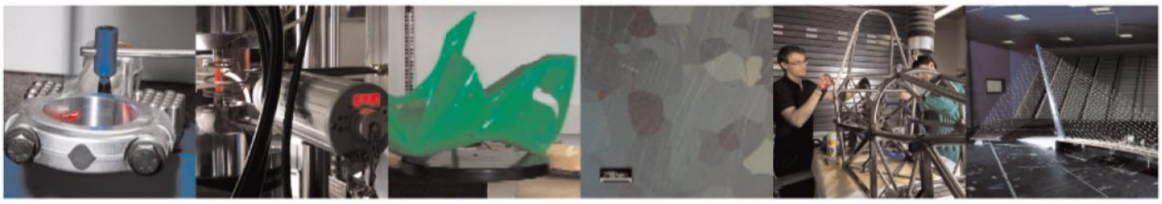

Restart policies to maximize production quality in mixed continuous-discrete multi-stage systems

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Restart policies to maximize production quality in mixed continuous-discrete multi-stage systems

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In sectors as semiconductor fabrication, pharma industry and food production, discrete production processes are intertwined with continuous production processes. Since continuous processes frequently produce large batches of material requiring fairly long processing times, restart policies aiming at scrap reduction especially due to work-in-progress perishability are commonly used to control the material flow in multi-stage production systems. A performance evaluation model integrating control mechanisms is proposed to assess the impact of local restart policies at system level. A real case study in the food production is presented, where the parameters of restart policies are optimized to maximize production quality.

Quality; Manufacturing system; Performance evaluation.

1. Introduction

In manufacturing systems, discrete production processes may be intertwined with continuous production processes. In stages characterized by continuous production, material is normally processed in large batches, usually by following a specific recipe requiring fairly long processing times with respect to the processing times occurring in the stages characterized by discrete production. The need of inter-operational buffers to decouple the stages is problematic due to the risk of deterioration of the stored material. Some industrial sectors are especially affected by this phenomenon. For instance, in semiconductor fabrication, pharma processing, food production and battery production, scrapping of in-process material is relatively high due to material perishability [1]. The reasons are manifold: some of the afore-mentioned processes are based on chemical or biological reactions and some reactions may happen also during the waiting time before the next stage [2], some materials are subject to contamination, which limits the time of exposure [3], some others involve thermal processes, where thermal parameters are related to waiting time or production parameters like machine load [4].

Continuous processes are traditionally characterized by very tightly pre-defined recipes which cannot be modified. Therefore the only control policies that can be adopted are restart policies which are meant to define the starting time of the processes in order to limit scrap.

In real plants, restart policies are normally developed and implemented by practitioners and operators, based on expertise and simple heuristics. This approach normally leads to local optimization of critical machines without taking into account interactions at system level, where stages may be strongly coupled [5]. As a result the best performance in terms of scrap and quality [6] are rarely attained. Therefore, to define restart policies, a stochastic approach is needed which takes into account randomness and evaluates the expected system level impact of local decisions.

The paper is organised as follows: the concept of restart policy and a novel performance evaluation model for mixed continuous-discrete production integrating state-based control mechanisms is presented in Section 2; in Section 3 a real case is introduced and discussed with respect to the problem formulation; numerical evaluations and results are commented in Section 4; conclusion and future research are discussed in Section 5.

2. Methods

2.1. Concept of restart policy in mixed continuous-discrete multi-stage systems

The aim of the work is to model and evaluate the impact of restart policies in multi-stage systems, characterized by mixed continuous-discrete production with scrap, in order to identify and select the policy which guarantees the best production quality.

A restart policy defines the condition which triggers a machine to stop and restart processing.

As an example, Figure 1 shows a two-stage manufacturing system, where the upstream machine is fast and reliable, and it processes discrete batches of parts. On the contrary, the second machine is slower and unreliable, and it gradually and continuously takes material from the buffer to process it. The buffer has finite capacity. If the buffer is full, the upstream machine cannot download the part and therefore it goes to the '*blocked*' state. Conversely, if the buffer is empty, the downstream machine cannot take material from the buffer and therefore it goes into the '*starved*' state (Figure 2b). A Blocking Before Service policy is applied, i.e. the first stage is prevented from starting to process a batch if there is not enough space in the downstream buffer to download it. Due to material perishability, when the second machine fails, the buffer content and the batch which is being processed by the upstream machine must be scrapped.

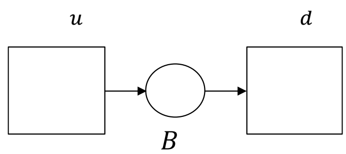


Fig. 1. Graphical representation of a two-stage system.

An excerpt of a sample path of the described system is shown in Figure 2, where the buffer content and the scrapped material is depicted in Figure 2a, and the sequence of machines states is depicted in Figure 2b.

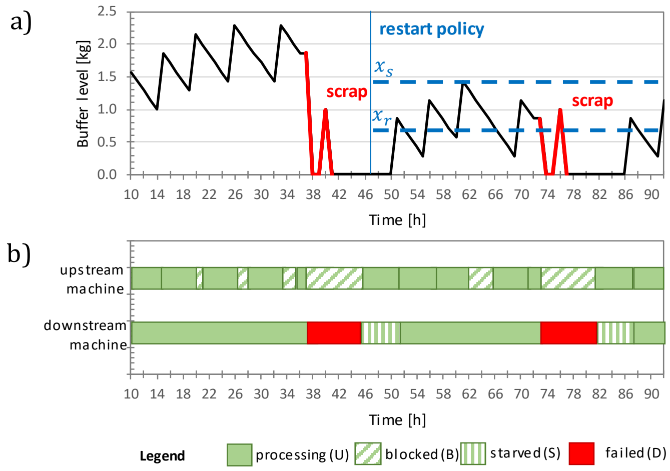


Fig. 2. Sample path of buffer content (a) and sequence of machine states (b).

On the left-hand side of Figure 2a, the system works without restart policies. As it can be seen, the buffer level goes up and down, due to the fact that the upstream continuous machine produces loads of material that are introduced in the buffer at specific times while the downstream discrete machine is processing the material in small quantities. As a general trend, the buffer level is growing due to the fact that the upstream machine is on average faster than the downstream machine. Therefore, after a short transient period, the buffer tends to be always almost full, and the upstream machine produces one batch, then it has to wait until enough space is available in the buffer, then it produces another batch and so on. This sequence is interrupted when a failure in the downstream machine occurs, as shown at time instant 35. At this point, the buffer content is scrapped, as it can be noticed with the first red steep line, and then the content of the upstream machine is downloaded in the buffer and it is scrapped as well (second small red line). The main problem of operating the system in the described way is that the buffer is almost always full and, as a consequence, the amount of material which is scrapped is quite high.

If a restart policy is adopted, as shown in the right-hand side of Figure 2, then the upstream machine is stopped when the buffer level exceeds a certain threshold x_s and it is allowed to restart when the buffer level goes below another threshold x_r. As a consequence, when a failure occurs, e.g. time instant 71, the material to be scrapped is less than in the previous case, while the throughput of the system remains the same as before. Therefore, restart policies help improving production quality, i.e. the throughput of good parts [7].

In reality, the situation is more complex than the one described. For instance, the upstream machine may also be unreliable, and therefore the thresholds x_r and x_s have to be set considering the risk of starvation of the downstream machine. In the latter case, the restart policy has to deal with the following trade-off: on the one hand, the idle time of the bottleneck downstream stage should be minimized, suggesting to keep a relatively high average buffer level, on the other hand, the scraps should be kept to the minimum suggesting to keep the average buffer level relatively low. In addition, in larger systems local decision may affect other stages of the line especially when scrap occurs as a consequence of blocking and starvation. Therefore, to define restart policies, a stochastic approach is needed which takes into account randomness and evaluates the expected system level impact of local decisions. Even if the example used so far might be reminiscent of some base-stock policies (e.g. (Q,R) policies), nevertheless the problem proposed is structurally different because it jointly addresses finite buffer capacity, stochastic perishability, multi-objective optimization, and it grounds on a state-based control policy.

2.2. Stochastic model integrating restart policies

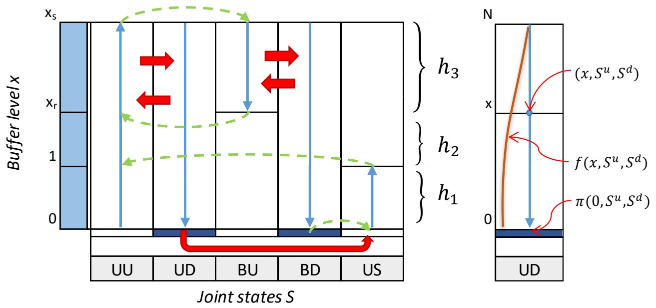
Few analytical stochastic models in the literature try to relate the quality to the production rate of the parts, studying in particular the influence of system parameters, such as repair times [8] and buffer capacities [9], on quality related performance such as the yield (fraction of good throughput over the total) and the lead time [10]. They deal with discrete synchronous manufacturing lines, which may or may not be characterized by deteriorating parts [11] and scrap [12]. Existing analytical stochastic models, however, do not address the integration of restart policies in the model, and do not deal with mixed continuous-discrete production.

In the following, a stochastic analytical model for the steady-state performance evaluation of mixed continuous-discrete production, integrating control mechanisms for the analysis of restart policies is introduced. The stochastic model is based on the state-based Markovian representation of the resources in the system. The joint state of the machines is the combination of the states (S^u,S^d) of the upstream and downstream machines; the buffer is a continuous variable x. Therefore, the system state can be described by the triplet $S=(x,S^u,S^d)$ as highlighted in Figure 3a and 3b. In particular Figure 3a shows the state-space representation of the example described in the previous Section. The discrete joint states of the machines are depicted horizontally (UU,UD,…) and the buffer level is depicted as continuous variable on the vertical axis.

Since the system may remain for some time on specific thresholds, those states are named 'accumulation points' and they are depicted as solid dark blue blocks in Figure 3a (e.g. state $S=(0,UD)$).

Joint machine states are dense with respect to buffer levels $0<x<N$ and they are indicated as blue arrow pointing in the direction of the buffer increasing or decreasing, according to the difference of production rates of the two machines in that joint machine state. Big red arrows represent the stochastic transitions among the various states, i.e. failure and repair rates, and they can happen at any buffer level or they can generate from an accumulation point. Dashed green arrows represent the controlled transitions that happen on hitting precise thresholds. These thresholds define ranges h_i where the system has different behaviour (in Figure 3a, three ranges h_1, h_2, h_3 are shown).

The state-based representation allows to describe the dynamics of the system. For example, when both the machines are operational (joint state UU in Figure 3a), the buffer tends to increase since the upstream machine is on average faster than the downstream machine. If the downstream machine fails, the content of the buffer and the material in the upstream machine is scrapped, therefore the joint state UD empties the buffer level quickly (blue arrow pointing down). Then the system goes in the state $S=(0,UD)$, while the upstream machine scraps its material and remains in that state until the downstream machine is repaired bringing the upstream machine to be operational again (red arrow leading to state US). Once the upstream is operational it starts processing a new batch, however the downstream machine remains starved, during the processing of the batch (joint state US). As soon as the batch is finished and downloaded into the buffer, a controlled transition (green arrow) activates the downstream machine which can start processing again (state UU). If both machines remain operational, sooner or later the buffer level exceeds threshold x_s and a controlled transition (green arrow) forces the upstream machine to stop and become idle (state BU). The upstream machine remains idle until the downstream machine brings the buffer to the level x_r; at that point a controlled transition (green arrow) activates the upstream machine bringing the joint machine state to UU. Therefore, the last two controlled transitions described model the restart policy.



a) b)

Fig. 3. Graphical representation of the system dynamics (a) and of the system characterization (b).

Even if, in the description of the state space, a temporal sequence of events has been mentioned, the goal of the model is to calculate the steady state probabilities of finding the system in the various states as a function of the thresholds x_s and x_r. Since the variable representing the buffer level is continuous, the state space has infinite states (x,S^u,S^d), therefore the goal is to calculate, for each joint state, the probability density functions $f(x,S^u,S^d)$ and the probabilities $\pi(x,S^u,S^d)$ of the accumulation states (Figure 3b), They can be found by solving the following linear system of differential equations and boundary conditions:

$$\begin{cases} \dfrac{\partial}{\partial x} f(x,S_h^u,S_h^d)\cdot diag[v(S_h^u,S_h^d)] = Q_h^T \cdot f(x,S_h^u,S_h^d) \\ \pi(S_h) = B1\cdot f(x,S_h^u,S_h^d)\cdot v(S_h^u,S_h^d) \\ f(x,S_h^u,S_h^d)\cdot v(S_h^u,S_h^d) = B2\cdot f(x,S_h^u,S_h^d)\cdot v(S_h^u,S_h^d) \\ \sum_h \sum_{S_h^u,S_h^d} \left[\int_x f(x,S_h^u,S_h^d)dx + \pi(S_h) \right] = 1 \end{cases} \quad \forall\, h \qquad (1)$$

Where:

- The first equation describes the system dynamics due to the random change of machine states. (transition rate matrix Q representing the red arrows in Figure 3) and the vector of production rates of the joint states $v(S_h^u,S_h^d)$;
- The second and third equations describe the dynamics due to the superimposed controls (matrixes B1 and B2 representing dashed green arrows in Figure 3) ;
- The fourth equation is the normalization equation.

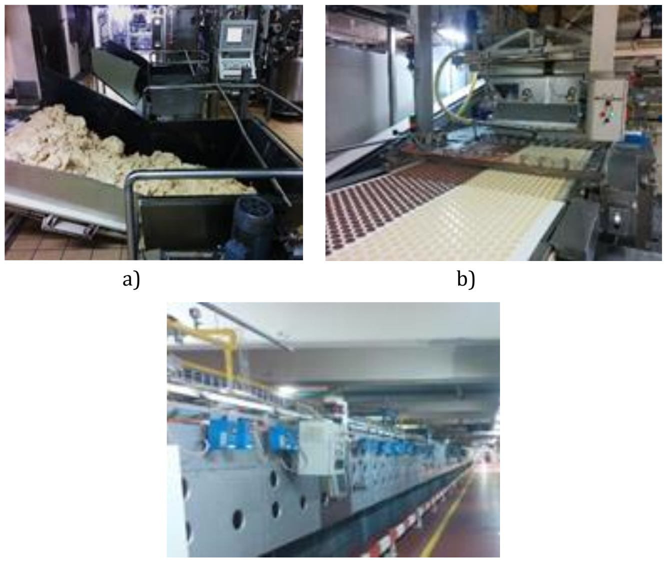
The system can be solved using the method proposed in [13] and the performance measures like the system throughput can be obtained:

$$th = \int_0^N \left(\mu^d \cdot f(x,UU) + \mu^d \cdot f(x,BU) \right) dx \qquad (2)$$

3. Real case study: cookie production system

3.1. Description of the multi-stage production system

The real system analysed is a cookie production line of a major Italian producer composed by three stages. The first stage is composed by two kneaders taking in input raw material according to a specific recipe (Figure 4a). First, a pre-dough (pre-operational state D_U) is obtained, then some final ingredients are added and the dough is completed to be put in the downstream buffer (operational state U). The downstream buffer has a capacity of three doughs. The second stage is composed by hoppers coupled with a forming machine (Figure 4b). Hoppers gradually take the dough from the buffer and dose it to the forming machine. The forming machine prints rows of cookies on a conveyor belt (operational state U). The third stage is a linear oven, characterized by a precise temperature distribution along the path that is called cooking diagram (Figure 4c). The oven contains 200kg of material and it can be considered to be perfectly reliable (one operational state U). After the oven, the cookies are put in a cooling buffer.



a) b) c)

Fig. 4. Overview of the multi-stage cookie production system.

3.2. Problems leading to scrap

The strongly coupled dynamics of the stages lead the system to frequent scrapping condition:

- **Kneaders:** If a failure happens while the machine is processing the dough, the dough must be scrapped and the process must start over again (failure state D).
- **Forming machine**: In case of any failure lasting longer than a specific duration (long failure D_L), the machine must be cleaned and the remaining dough in the upstream buffer must be scrapped. As a consequence, if the kneaders are processing a dough, also the dough in the kneaders must be scrapped. On the other hand, if the kneaders are processing a pre-dough, the pre-dough does not need to be scrapped. In case of minor failures in the forming machine, there is no need to scrap (short failure D_S).
- **Oven**: If the amount of cookies in the oven is below a certain threshold (one/third of the oven capacity), the cookies become scrap due to overcooking.

3.3. System controls for production quality

Two alternative restart policies can be implemented and evaluated within the production system:

- **P1**: When the kneading machine is idle (B), and the buffer is decreasing, there is a threshold level x triggering the kneading machine to start over a new dough.
- **P2**: When the forming machine is idle (S), and the buffer is increasing, there is a threshold level x triggering the forming machine to start over the forming operation.

The problem is complex: on the one hand, the aim of decreasing the scrap of the in-process inventories could lead to keep as low as possible the buffer level; on the other hand, this policy might lead to starvation of the forming machine increasing the risk of low filling of the oven which leads to scrapping parts at the end of the oven, due to overcooking. In Table 1, the case study is summarized in terms of behaviour of the machines, scrapping conditions and available restart policies.

Table 1 Summary of the description of the use-case.

Stage dynamics	**Scrap**	**Restart policy**
Kneaders: D_U: kneading of the pre-dough U: kneading and completion of the dough D: failure	If the kneading machine fails (state D). If the machine is completing the dough (state U) and the buffer is being scrapped.	P1: Restart of the pre-dough when idle.
Forming: U: cookie forming D_S: short failure D_L: long failure	If the forming machine fails in the long failure mode (state D_L), the buffer must be scrapped.	P2: Restart of the forming operation when idle.
Oven: U: cooking	If the oven contains less cookies than a specific threshold, cookies are scrapped at the end.	

4. Results

By using the proposed method, the two policies can be compared with respect to the throughput of good parts and the percentage of scrap. In particular, it is possible to use the proposed methodology as a decision support tool for the production line control. Indeed, according to the context, different goals might be set: one possible goal when demand is very high could be to maximize the throughput of good parts, another goal when demand is stable could be to minimize scrap for a specified throughput rate.

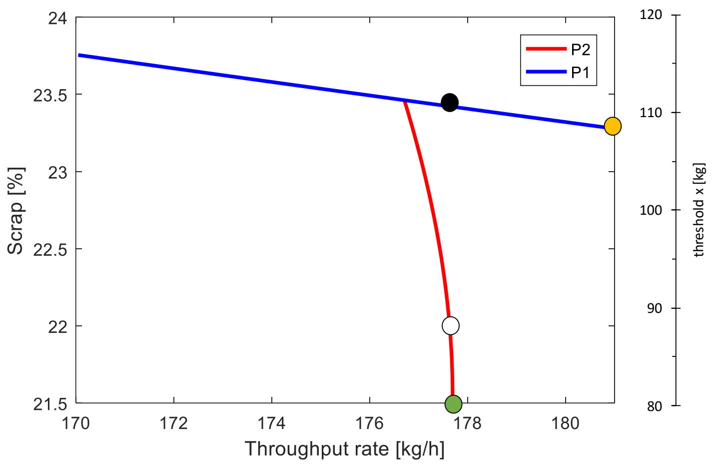


Fig. 5. Production quality in terms of scrap percentage and throughput rate for the two restart policies.

In Figure 5 the production quality in terms of good throughput (x axis) and scrap percentage (y axis) is compared for the two alternative policies P1 (blue line) and P2 (red line). The points on the two curves can be obtained by changing the level of the thresholds (right scales on the graph). Currently, the company is operating with restart policy P1 for a buffer threshold equal to 2 doughs (110 kg), leading to a throughput rate of about 178 [kg/h] and a total scrap percentage of 23.5% as highlighted by the black dot in Figure 5. However, the same throughput could be obtained by substituting policy P1 with policy P2 with a threshold equal to 90 kg (white dot). This would lead to reduce the scrap percentage to 22%. Even better policies are indicated by the green dot (Th=178 [kg/h] and scrap 21.5%) and orange dot (Th=181 [kg/h] and scrap 23.3%) which both increase the throughput and reduce scrap in comparison with the current policy. The comparison shows that the green dot obtained with policy P2 is to be preferred in case of minimization of total scrap; on the other hand, the orange dot obtained with policy P1 is to be preferred if throughput of good parts needs to be maximized.

5. Conclusions and future work

This paper presents a novel stochastic model for the performance evaluation of systems characterized by mixed continuous-discrete production, and it integrates control mechanisms in order to assess the impact of restart policies. Restart policies aim at improving production quality in terms of throughput and scrap in production systems characterized by tightly defined processes and perishable in-process material.

A real case in the food sector shows the improvements that can be reached with the implementation of the correct control policy. In fact, the proposed model provides a valid decision support methodology for the production line control. The evaluation of the restart policies shows that, according to the context, different policies pursue different goals in terms of throughput and scrap.

In this way, the advantages of using a model capable to provide simple rules in a complex context has been shown. Indeed, a company can easily implement the right policy according to the needed objective. Moreover, the proposed methodology can be used as a kernel for multi-objective optimization problems addressing production quality. Further research can be devoted to the analysis of the interaction of restart policies in multi-stage manufacturing systems characterized by more complex dynamics.

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