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A threshold-based control policy for scrap reduction of perishable in-process inventories

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Abstract

Sustainability has become a key factor for competitiveness. Sustainable production strategies aim at the scrap reduction of in-process inventory. In some sectors such as food or pharmaceutical sector, in-process inventories must be scrapped after a certain time due to perishability. Therefore, local policies are usually applied to machines in order to mitigate the impact of disruptive events leading to scrap.
This work presents an analytical model for the performance evaluation of two-machine lines which integrates a threshold-based control policy for the scrap reduction grounding on the joint system dynamics. Results show that the proposed integrated policy performs better than local policies with respect to the scrap reduction without major losses in throughput. Moreover, it is shown how considerations about operating control policies can be beneficially included in the system configuration phase.

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Keywords: Manufacturing system, Sustainable development, Control policy

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1. Introduction

In the last decade, sustainability has become a pillar of modern society and economic development. It affected not only economic and societal growth, but also the industrial sector. Indeed, competitive and sustainable manufacturing has been addressed as one of the main enablers for the sustainable development [1].

Therefore, high-added value, knowledge-based, manufacturing companies have recognized that sustainability is a key factor for competitiveness. However, sustainability itself includes a wide range of aspects, that can range from the energy management to human resources valorization to sustainable operations. For manufacturing companies, being capable of a sustainable production system means being capable to face the current challenges of delivering high-quality products with the required production rates, while minimizing the use of resources [2]. Indeed, in recent years an integrated vision of manufacturing systems management and engineering has made its way, in order to analyze and show the relation among the three fundamental functions of manufacturing, which are quality, maintenance and production logistics [3]. Traditionally, these areas have been treated separately by researchers and practitioners, but it is clear that they strongly interact. In fact, recent technological innovations such as smart sensors and information management solutions, make possible

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the implementation of advanced integrated strategies for sustainable manufacturing.

As mentioned above, when it comes to high-added value production, quality and resource efficiency play a relevant role in the overall system management. Hence, sustainable manufacturing strategies aiming at increasing the product quality and decreasing the scraps have been studied and implemented, such as zero-defect oriented strategies.

However, in some sectors scraps are unavoidable. For example, many of the production processes like the food industry, pharmaceutical production and battery and semiconductor manufacturing, are characterized by scraps due to in-process perishable inventories, without any, or negligible, possibility of rework or recycling [4]. The reasons are many: mainly, the afore-mentioned processes are based on chemical reactions, which need a very precise timing and a fixed recipe. Therefore, these processes are traditionally stable, meaning that a change in the process parameters might take time and not be able to guarantee the same performance.

Nevertheless, this is why an integrated analysis of systems characterized by in-process perishable inventories, aiming at scrap reduction, is important. In the following, an analytical model of a two-stage line where in-process inventory must be scrapped when the downstream machine is stopped for a long failure is considered. The proposed policy aims at quantitatively assess the scrap reduction in two-stage manufacturing systems, providing considerations that can be useful in the configuration phase.

This work is structured as follows: first, the state of the art for the relevant problems regarding perishability in industrial sectors and the performance evaluation models for product quality are presented; second, the reference system and the performance evaluation model are introduced; third, alternative control policies based on single-machine dynamics and joint system dynamics are characterized and numerical results are analyzed; finally, the conclusive part includes the last comments and future research.

2. Literature review

In this work two main topics from the state of the art are addressed: from the industrial viewpoint, works describing the problem of perishability in specific industrial sectors, and from the modeling viewpoint, performance evaluation models dealing with product quality and scrapping. These two topics are discussed in the following sections 2.1 and 2.2.

2.1. Perishability in production systems

All products are characterized by perishability. Indeed, most of the literature is related to the analysis of perishable inventories in the overall supply chain, see for instance the comprehensive reviews over the years [5]-[8]. However, not many works are devoted to the perishability of the in-process inventory [9]. In fact, in some industrial sectors, perishability has a high negative impact on the production sustainability, and it might lead to scrap the product. The reasons for scrapping might be several, and directly linked to the production process:

- The pharmaceutical sector is characterized by intrinsic perishability, given that the production is a chemical process requiring specific recipes and precise work orders. Usually, an upstream part performs chemical operations on a continuous flow of product, which is then processed in form of pills or bottles by a downstream part. Afterwards, there is a final stage dedicated to the packaging. Therefore, a scrapped product represents not only a waste, but also a liability, since in most of the cases it is a harmful product. Production policies to prevent the disposal of perishable pharmaceutical products have been studied [10].

- In food processing industries, products and in-process inventory are highly exposed to perishability, due to hexogen and healthy factors. These production systems usually include a first stage where the primary input is processed, i.e. milk for dairy products or the dough for baked products, then it overcomes a thermal process, i.e. an oven, which is usually the bottleneck. In this sector the scrapped product, though having a low monetary value, has a high sustainability value and food waste is discouraged [11].

- Electronic production, such as the semiconductor fabrication, is a complex manufacturing process. The production flow is barely linear on a macro-level, but it includes linear sub-system, where the timing and the consequences of a downstream long stoppage may cause the rework or the scrap of the in-process inventory (see for instance, but not only, the diffusion operation, in [12]). Moreover, electronic in-process inventories have a high value and local production policies are devoted to maintain them low in order to reduce the parts' disposal [13].

2.2. Performance evaluation models for product quality

Analytical models allow a deep analysis and general considerations on production mechanisms. In the last years, quality has been considered as relevant aspect in the models for performance evaluation of manufacturing systems. Therefore, many works have been devoted to the integration of quality-related policies in the overall system model. Efforts have been made in the integration of scrapping policies in multi-stage automated lines, such in [14], [15] and [16], where scrap flow is treated as a separate flow with respect to the good throughput. The relation between system parameters and quality performance has been investigated in [17] and in [18], where it is shown the effect of the buffer size on the production yield, i.e. percentage of good production on the total. Indeed, the marginal throughput increment decreases with respect to the buffer size, whereas the scrap rate increases linearly, because it is proportional to the average inventory level. This relation is used in [19] to determine the optimal buffer size that minimizes the lead time. In fact, a trade-off does exist between scrap rate and effective throughput, for which the optimum is found where the marginal gain in the throughput does not compensate anymore the scrap rate. In [20] the effect of parts' scrapping caused by long failures on the system parameters is investigated, and applied to an example in the food sector. Other applications have covered the pharmaceutical production [21], and the painting process of an automotive system, where the quality-bottleneck is systematically identified and improved [22].

3. Description of the reference system

The reference system is composed by two machines decoupled by a buffer with finite capacity. The upstream machine M^u takes raw material as input, processes it and loads it into the buffer, where the downstream machine M^d takes it and processes it to deliver the final product. In the graphical representation, machines are represented as square and the buffer as a circle (Fig. 1).

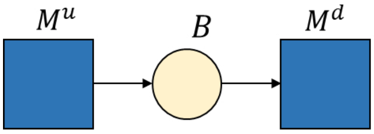

Fig. 1. Two-machine line

Both machines are unreliable, i.e. they can fail while they are operational. In particular, the downstream machine is characterized by short and long failures. When a long failure occurs, the in-process inventory stored in the buffer must be scrapped, due to perishability, as soon as the downstream machine has been repaired [20].

3.1. System model and performance

The system model grounds on [23], where an analytical model for a two-machine line with machines having a different behavior according to the buffer level is presented. Each machine is described by a continuous-time Markov Chain having a set of discrete state $S^k, k = u, d$ characterized by a vector of production rates $\mu^k, k = u, d$.

The upstream machine M^u has a set of states $S^u[i], i = 1,2$ characterized by a vector of production rates $\mu^u = [\mu(1)\ \mu(2)]^T$. When the upstream machine is operational, i.e. in state $S^u[1]$, the production rate $\mu(1) \neq 0$; when it is failed, i.e. in state $S^u[2]$, the production rate $\mu(2) = 0$. Failure rate p^u and repair rate r^u define the transition rates among states, as depicted in Fig. 2.

Similarly, the downstream machine M^d has states $S^d[i], i = 1,...,6$ characterized by a vector of production rates $\mu^d = [\mu(1) \ldots \mu(6)]^T$. States $S^d[1]$ and $S^d[2]$ are operational states, i.e. the downstream machine processes good parts with production rate equal to $\mu(1) = \mu(2) = \mu_G^d$. Two failure types might occur: state $S^d[4]$ and $S^d[5]$ represent the frequent and short micro-stoppages (S), and state $S^d[6]$ represents the less frequent and long failure (L).

After a long failure occurs and the machine is repaired, the buffer content is emptied by the downstream machine with scrapping rate $\mu(3) = \mu_B^d$ and all the parts are scrapped. This state is represented by state $S^d[3]$. Therefore, a control on the lower boundary forces the machine to leave state $S^d[3]$ only when the buffer level is equal to zero. After a long failure and the scrapping state, the downstream machine is restored to its initial condition. Transition rates characterizing the Markov Chain are depicted within Fig. 2

The buffer has finite capacity equal to N and is described by the continuous variable x. Therefore the system state is described by the triple (x, S^u, S^d).

For each transition, rates are defined as the inverse of the correspondent Mean Time. The overall graphical representation of the mixed-state Markov Chain of the two-machine line is represented in Fig. 2, where the controlled transition is defined by the dash line.

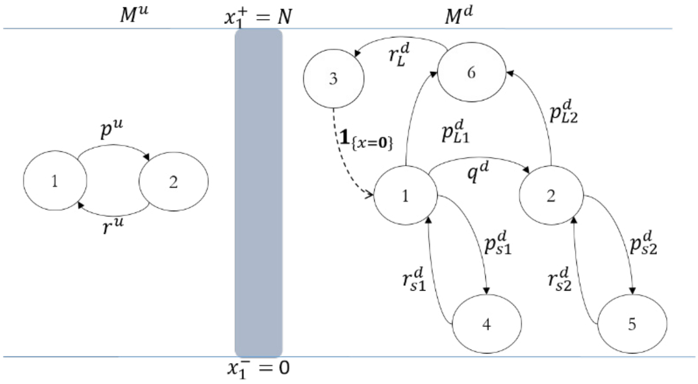

Fig. 2. Markov Chain graphical representation of the two-machine line.

The relevant performance measures are represented by the throughput of good parts *Th*, the scrap throughput *ThS*, the average inventory level $\bar{n}$, and they are defined as follows:

$$Th = \mu_G^d \cdot \sum_{j=1,2} \pi(S^d[j])$$

$$ThS = \mu_B^d \cdot \pi(S^d[j]), j = 3$$

$$\bar{n} = \int_{x=0}^{N} x \cdot f(x, S^u[i], S^d[j])dx$$

where $\pi(S^d[j])$ are the steady state probabilities of state $S^d[j]$ and $f(x, S^u[i], S^d[j])$ represents the probability density function of the system state $(x, S^u[i], S^d[j])$.

Then, we are interested in the system yield *Y*, defined as the percentage of effective throughput on the total throughput, and the complementary value *YS*, which represents the percentage of scrap on the total throughput.

$$Y = \frac{Th}{Th + ThS} \quad YS = \frac{ThS}{Th + ThS}$$

3.2. Analysis of the system with no control policy

In this section a reference system with realistic parameters is analyzed in order to understand the dynamics leading to the scrap throughput. Parameters can be found in Table 1.

Table 1. System parameters.

	Transition rates [1/t.u.]	Production rates [p/t.u.]
M^u	$p^u = 0.01; r^u = 0.1$	$\mu^u[1] = 2.7$
M^d	$p_s = 0.035; r_s = 0.5; p_L = 0.0045$ $r_L = 0.02; q = 0.01$	$\mu_G^d = 2.5; \mu_S^d = 10$
B	N=1:100 [p]	

As in many real system described in Section 2.1, the downstream machine is the bottleneck with respect to the production rate. The system is analyzed with respect to the buffer capacity.

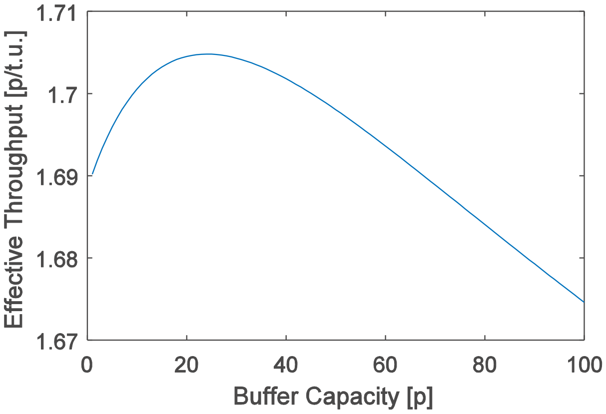

Fig. 3. Effective throughput vs Buffer capacity

In Fig. 3 the effective throughput is shown. The effective throughput curve presents a maximum when the buffer capacity is 25 parts. This happens because, as well known, the throughput is a monotonically increasing function with respect to the buffer size, with a marginal decreasing gain.

On the other side, the average inventory level is linearly increasing with the buffer size, therefore the scrap throughput increases linearly as well, since it depends on the buffer content.

The result of the combined effect is that a trade-off does exist between buffer capacity and effective throughput, as explained in details in [19].

This consideration is useful in the phase of system configuration, but the detailed machine dynamics are often not known until the system is operational, therefore the buffer capacity might have not been optimized for quality purposes.

Moreover, in the aforementioned industrial sector, the capability of the system is represented not only by the effective throughput, but also by the scrap yield. Indeed, it is important, for sustainability reasons, to minimize the scrap production on the overall throughput. Usually, control policies are implemented once the system is operational, based on heuristics and common sense.

4. Definition of the policies

In this section, two alternative control policies for the system improvement are defined, with respect to the case when no control is implemented, as explained in Section 3.2. The first policy corresponds to what is currently a best practice in manufacturing and it is a local control policy implemented on the upstream machine, while the second policy is still implemented on the upstream machine, but it grounds on considerations about the joint system dynamics.

4.1. Local policy P1

When the buffer increases and hits a threshold x^u, the upstream machine is prevented to release the parts in the buffer for a fixed amount of time equal to $1/r_{sb}$. The Markov Chain of the upstream machine is modified as follows: a stand-by state $S^u[3]$ is added, which is triggered by a control action represented by the dash line. This policy is motivated by the consideration that if the upstream machine is faster than the downstream machine, the buffer will tend to be always high, therefore when a long failure happens, it is more likely that the whole buffer content is scrapped. In fact, in this way the capacity of the buffer is equal to x^u, since the system cannot reach any buffer level $x > x^u$.

4.2. Threshold-based joint-state policy P2

When the buffer increases and hits a threshold x^u and the downstream machine is in state $S^d[2]$ or it is failed, the upstream machine is prevented to release the parts in the buffer for a certain amount of time equal to $1/r_{sb}$. The Markov Chain of the upstream machine is modified by adding a stand-by state $S^u[3]$, which is triggered by a control action based on the joint system-level Markov Chain.

The resulting system changes its behavior according to the buffer level. Indeed, when the system is in state $(x < x^u, S^u[1], S^d[2])$, the buffer level is increasing and as soon as the threshold x^u, the system state changes immediately to $(x < x^u, S^u[3], S^d[2])$ and the buffer level starts decreasing because the upstream machine is in stand-by and the downstream machine is still operational. Similarly, when the system is in state $(x < x^u, S^u[1], S^d[4,5])$, the buffer level is increasing and as soon as the threshold x^u, the system state changes immediately to $(x^u, S^u[3], S^d[4,5])$ and the buffer level stays in the same level because the upstream machine is in stand-by and the downstream machine is failed.

This policy grounds on the joint system dynamics, and it exploits the information about the system state to decrease the buffer level when it is more likely to end up scrapping. Indeed, the policy can be defined as a *selective hedging point*, since the upstream machine is avoided to produce too much with respect to the scrap risk. In fact, when the downstream machine is in state $S^d[2]$, it is more likely to go into the long failure, and causes the scrapping of the entire buffer content. However, the implementation of this policy may cause losses in the effective throughput, since if the upstream machine is put in stand-by when the buffer level is not adequate, its failure may cause starvation to the bottleneck. Conversely, when the downstream machine is in state $S^d[1]$, the probability that a long failure occurs is low, by definition, therefore it is more convenient for the system to keep on producing in order to avoid losses in the effective throughput.

Therefore, an intermediate threshold should exist, according to the duration of the stand-by state imposed to the upstream machine, for which the scrap percentage is minimum.

5. Analysis of the policy P2

In this section, the policy P2 is first analyzed and then compared to the policy P1 and to the no-control case.

The experiment analyzes how the threshold x^u influences the Scrap Yield *YS*, for different duration of the stand-by state imposed to the upstream machine. Data are provided in Table 1, the buffer capacity is set to N=100. The resulting graph is shown in Fig. 4 and Fig. 5.

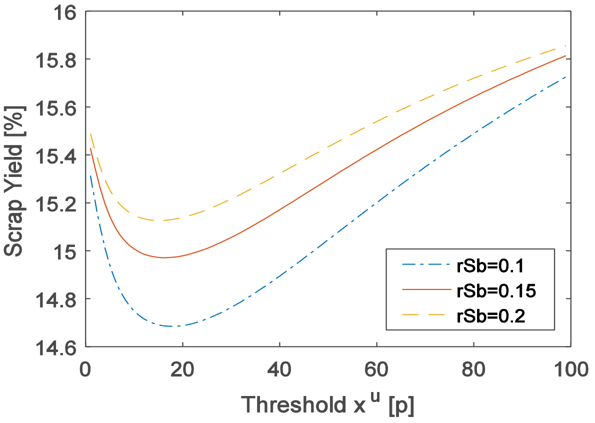

Fig.4. Scrap Yield YS for threshold xu=1:100.

- The function has a global minimum for *YS* in a threshold $0 < x^u < N$. High stand-by durations $1/r_{sb}$ bring to scrap less. In fact, the more time the upstream machine is stopped, the more the buffer level decreases due to the downstream machine being operational. Therefore, when the long failure occurs, the scrap quantity is low.

- In Fig. 5 the Effective Throughput with respect to the threshold is shown. It shows that implementing the policy outside the optimum threshold in Fig. 4, might impact in very different ways the Effective Throughput. If the policy is implemented too soon, not only the Scrap Yield is high, but also the Effective Throughput is low, because the stand-by causes starvation to the downstream machine, which is the bottleneck. If the policy is implemented for high thresholds, the Effective Throughput is high, but also the Scrap Throughput is high, therefore the result is that the Scrap Yield is high.

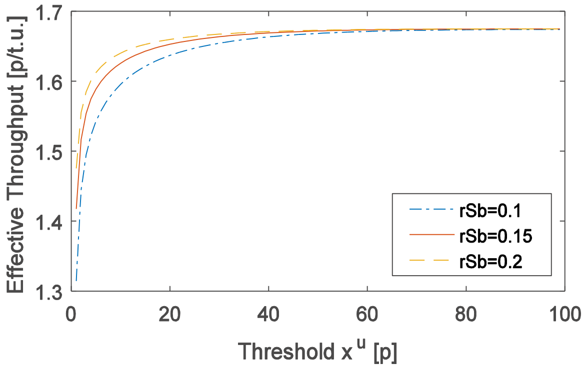

Fig.5. Effective throughput Th for threshold xu=1:100.

- In Fig. 5 it is possible to notice also that the duration of the stand-by $1/r_{sb}$ has an opposite effect on the Effective Throughput: the longer it lasts, the lower the Effective Throughput is.

5.1. Comparison among policies

In this Section, the proposed policy P2 is compared with the policy P1 and the no-policy system, in two cases: in the first one, the buffer size is high, as if the buffer size had not been optimized with respect to the Effective Throughput; in the second one, the buffer size is equal to the optimal buffer size with respect to the Effective Throughput (see Fig. 3). Data are provided in Tab. 1.

Table 2. Comparisons among policies.

		No control	Policy P1	Policy P2
N=100	EffectiveTh[p/t.u.]	1.675	1.675	1.675
x^u=18	ScrapTh[p/t.u.]	0.32	0.31	0.25
	Scrap Yield YS[%]	16.1	15.7	12.9
N=25	EffectiveTh[p/t.u.]	1.705	1.684	1.680
x^u=8	ScrapTh[p/t.u.]	0.09	0.08	0.06
	Scrap Yield YS[%]	5.1	4.5	3.4

As it can be noticed from Table 2, the policy P2 guarantees always better performance with respect to the Scrap Throughput ThS and to the Scrap Yield YS, with an average gain of more than 2%.

- For large buffers, i.e. when the buffer size has not been optimized with respect to the Effective Throughput, the scrap reduction is more than the 3%, without any loss in the Effective Throughput. This can be explained as follows. When the buffer is large, the marginal gain of the Scrap Throughput with no control is higher than the one in policy P1 and in policy P2. However, policy P1 does not influence enough the buffer level, and the scrap reduction is negligible. Policy P2 decreases drastically the marginal gain of the Scrap Throughput by avoiding the buffer level to grow too much when the risk of scrapping is higher.
- When the buffer size has been optimized with respect to the Effective Throughput, the implementation of both policy P1 and P2 are detrimental for the Effective Throughput, with losses of 1.2% and 1.4% respectively. However, the scrap can still be reduced by the policies, but, when the policy P1 is implemented, the scrap reduction is only of 0.5% with respect to the Scrap Yield of the no control case. When the policy P2 is implemented, the scrap reduction is equal to 1.7%, which means that it is higher than the loss in the Effective Throughput.

6. Conclusion

This work presents an integrated control policy based on the joint machines and buffer dynamics aiming at the reduction of scrap throughput in a system where the in-process inventories are perishable and they are scrapped after a long failure in the downstream machine. The proposed policy is analyzed with respect to the decision variables, i.e. the buffer level triggering the policy and the duration of the stand-by imposed to the upstream machine when the downstream machine is going to fail for a long time with a higher probability.

The proposed policy is compared with another control policy, which is based only on the local dynamics between the upstream machine and the buffer, that is a current industrial best practice, and a base case when no control is implemented, but the system configuration has been optimized to have the maximum effective throughput. Results show that the proposed policy performs better with respect to the scrap reduction in each case.

The presented model can be further enlarged and analyzed under different viewpoints. First, a deeper analysis is required, in order to understand the impact of the other system parameters on the scrap reduction, such as repair and failure times. Second, the model can be enlarged by integrating other stages in the system, in order to understand the impact of the proposed control policy to the upstream and downstream part of the two-machine line. Finally, it is important to understand whether the scrap reduction does worth compared to the effective throughput reduction that might occur. Therefore, the policy should be optimized with respect to the trade-off between the scrap value and the final product value.

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