



## Modeling and Analyzing Supporting Systems for Smart Manufacturing Systems with Stochastic, Technical and Economic Dependences

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### ABSTRACT

Smart manufacturing systems are triggering the next industrial revolution. They are intended to be collaborative manufacturing systems that respond in real time to meet the system's changing demands and conditions. Different types of dependencies among system components are introduced to enable this and to improve system performance, including structural, stochastic, technical and economic dependences. Supporting systems are also introduced to this aim, through specified interfaces. In this paper, the role of maintenance policy, spare part inventory and buffer size as supporting systems of smart systems is considered. Load-sharing dependence, adaptive control with feedback and economic dependence are specifically considered, and their effect is studied via Monte Carlo simulation. Results show that smart systems with properly designed supporting systems have undoubtedly increased system complexity and dependencies, but can indeed increase availability and production volume, and system efficiency overall, with total cost reduced.

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### NOMENCLATURE

A	System availability	Shc	Shut down cost
Alfa	The scale parameter of the weibull distribution	$SL_i$	the stress level during the i-th duration
C	Cost	t	time
$CI_i$	the production cost of the i <sup>th</sup> machine	T	Working time
$CS_{ij}$	the spare part cost	TC	the total cost
$CR_{ij}$	the replacement action cost	V	The production volume
m	Nuber of stopping times	<b>Greek Symbols</b>	
n	the number of spare parts for a machine	$\mu$	The mean
$R(t)$	The reliability of component	$\sigma$	Standard division
STC	Store cost		

## 1. INTRODUCTION

Over the past decade, the topic of Smart Manufacturing (SM) has been more than a conversation among thought leaders, manufacturing experts and world-class companies: it has become a concrete initiative all over the world. Different definitions have been proposed for SM, such as the recent one from a leading organization like the National Institute of Standards and Technology (NIST) [1]: Smart Manufacturing systems are systems

that are “fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs.” The shared view is that the smart manufacturing system covers all subjects from A to Z for component production and employs computer controls for high levels of adaptability. For this, different types of dependencies are introduced in the system to enable communication among manufacturing machines and improve production volume; but the complexity and

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vulnerability of the systems are significantly increased, also.

Besides, supporting systems, such as maintenance and spare parts inventory, influence the effectiveness of the smart manufacturing system, and must be smart too. Maintenance costs can rise up to sixty percent of the production costs and up to a third of these costs may be due to unnecessary or poorly executed maintenance [2]. In a smart manufacturing system for enhancing performance and solving existing and future problems, all machines are monitored, data are collected and analyzed to predict and prevent performance degradation and potential failures. Big data, complicated dependencies among sub-systems and conflicting requirements pose challenges to this system; and render its management difficult. The different studies have been conducted in this field that in the rest of this section, some of these studies on maintenance and structure dependence, spare parts and maintenance, and buffer as a balancer in production lines are reviewed.

*Maintenance policy:* In recent years, several studies about maintenance policies and supply chain for smart and intelligent systems have been conducted. Cheng [3] used a Neural Network to predict the remaining useful life (RUL) of a multi-component system, in which economic dependence exists among the components. The proposed method included two-level failure probability thresholds, based on which Condition-based Maintenance (CBM) was applied. Zhou et al. [4] studied a system with economic dependence and high maintenance cost. Tian and Liao [5] applied a proportional hazards model to optimize system maintenance with monitoring and CBM. Bian and Gebraeel [6] investigated a multi-component system with degradation rate interactions and proposed a method for stochastic modeling and real-time prognostics. Opportunistic CBM strategies for systems with economic dependencies and redundancy was considered by Keizer et al. [7]. Zhang and Zeng [8] studied an identical multi-unit system to find the best periodic condition-based opportunistic preventive maintenance and safety policy for spare parts management. Minou et al. applied Markov Decision Processes to determine the optimal replacement time that minimizes the long-run average cost per time unit [9]. They investigated a load-sharing system with economic dependence and demonstrated that the load sharing effects among components could lead to a significantly more expensive maintenance policy. Other studies can be found in the literature on CBM modeling and optimization [10].

*Spare parts inventory management:* we know that maintenance effectiveness depends on spare parts inventory management. Spare parts inventory influences the maintenance cost and system availability. Thus, its relevant characteristics should be considered, such as ordering and replacement times, storage condition,

logistics problem. Some studies have been performed for joint optimization of spare parts and maintenance [11, 12]. Wang et al. [13] modeled the spare parts for a system monitored during operation. They found the optimal preventive maintenance threshold to satisfy the spare parts support requirements. Lin et al. showed that condition-based inventory policy increases about twenty percent of the system efficiency [14]. Auweraer and Boute proposed a method to forecast spare part demand based on service maintenance information [15]. Driessen et al. [16] proposed a framework for maintenance and spare parts planning and control; focused on demand and spare parts ordering to conduct the optimum maintenance.

*Buffer influence:* In industrial practice, production rates of machines may be changed, or machines may be preventively stopped for maintenance, but the production line stability and balance should be kept. In this situation, other machines continue their work to produce the products. For this, buffers are installed as intermediate storages to overcome the unbalancing and fluctuation. Buffer size and location optimization in a production line have been studied as an NP-hard optimization problem [17], from the production point of view. For example, Lutz et al. [18] applied scheduling policies and dispatching rules to determine buffer size and location. Weiss et al. [19] considered the buffer allocation problem, providing a review about this challenge and categorizing the previous studies, characteristics of flow line, objectives function and constraints, and solution method. Gan and Shi [20] studied a simple series system with respect to the spare part ordering problem of the upstream machine and buffer level, within the maintenance optimization of the downstream machine.

As mentioned in the literature, a production system performance and availability depends on system configuration, maintenance policy and spare parts inventory. The literature shows that these topics are deeply separately studied, but their simultaneously influences have been received less attention. Therefore, this dependence should be considered for adequate modelling and analysis. We investigate this topic in this paper, and present a method for modeling this relationship. In our study, smart manufacturing systems under Preventive Maintenance (PM) and CBM policies with load-sharing, series structure and economic dependencies are considered, and the influence of the important characteristics on the system performance is explored. Load-sharing structure is a complex dependence in the system behavior modelling, and the previous studies usually consider the simpler structures such as series or parallel configuration. Another contribution is the study on an adaptive control to decrease buffer influence, reduce total cost and improve system availability. Also, it can be said that the main contribution is considering different types of

dependencies (stochastic, technical and economic) in the system modelling.

In the next section, a manufacturing system is defined, and its structure and dependencies among components are illustrated. In Section 3, a method for system modeling is proposed and a simulation method to determine system availability and total cost is presented. In Section 4, the influence of the most important parameters on the system performance is investigated and the results of the simulation are presented. In Section 5, the results are discussed and the advantages and drawbacks of the proposed method are discussed, and directions of the future studies are suggested.

## 2. SYSTEM DEFINITION

Production systems layout is designed primarily based on the production processes which are necessary to make a product and their efficiency. Different structures and dependencies are used in industrial manufacturing systems. The series structure is often applied for sequential and multi-machine system installation in a production line. Each element of the series structure may consist of more than one machine. Buffers are used as intermediate storage spaces to increase production line stability. Indeed, the production rates of the machines are not equal and when a machine is stopped due to preventive maintenance or shortage of input materials, other machines work and their product should be stored. When the stopped machine operates again, the stored parts are consumed. Consider, for example, a smart manufacturing system (Figure 1) that consists of two stages: upstream and downstream. Four machines are used in upstream with series-parallel structure and load-sharing dependence. Load-sharing structure allows keeping the system performance at the desired level. For example, when M1 or M2 is stopped, this section is stopped, but another parallel-section (M3&M4) continues its operation, although under higher load than before. In this situation, the stress on the components may also be higher and the probability of failure of the active machines may be increased.

A machine is used in the downstream stage to adjust the production rate according to the output of the upstream stage. In the smart manufacturing system, when the amount of workpieces in the buffer is less than a specified value, a trigger signal is sent to reduce the downstream production rate, and another signal is created to increase production rate when the amount of workpieces in the buffer is more than the predefined threshold.

Also, in such smart manufacturing system, all machines are monitored, and data are collected to evaluate their state and predict the RUL of the critical

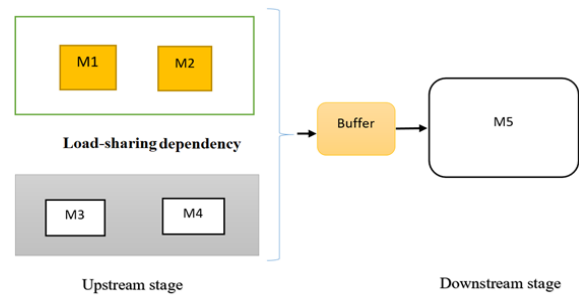


Figure 1. System structure

units that are most prone to failure. In this system, it is assumed that Weibull distributions describe their stochastic lifetimes. Depending on the reliability of the units, ordering and replacement times of spare parts are defined. Also, preventive maintenance is conducted based on a scheduled plan, as specified for each section of the system. Moreover, opportunistic maintenance is considered for cost reduction and increase of system availability.

## 3. SYSTEM MODELLING

In this section, the proposed framework for system modeling and performance determination is described. In this framework, the reliability is considered as a critical item for decision making in maintenance and spare parts management and decreases the system costs. Thus, reliability function and its variation according to the system structure are introduced, then the system logic is described and finally the proposed flowchart is presented in the next sections.

### 3.1. Component Reliability

In this paper, a complex structure is studied that can adapt production rate based on the system state. As a consequence, the stress on a machine may change and so does the expected lifetime; reliability is, then, calculated based on the conditional reliability formula (Equation (1)).

$$R(\tau|t) = \frac{R(t+\tau)}{R(t)} \quad (1)$$

where  $R(\tau|t)$  is the component reliability of a component that has worked until  $t$  and should continue to work for a duration  $\tau$ ,  $R(t)$  is the component reliability at the specified time  $t$  and  $R(t + \tau)$  indicates the component reliability at the end of the stress duration time  $(t + \tau)$ . If the stress level has varied in  $q$  instances before this time, the reliability is calculated as follows:

$$R(t + \tau) = R(\tau|t) \times (\prod_{i=0}^q R(t_{i+1}|t_i)) \times R(t_0) \quad (2)$$

The time duration of each stress level  $i$  is defined as  $(t_i, t_{i+1})$ , and  $t_{q+1} = t$ .

In this study, the RUL of a component is modeled by a Weibull distribution and when the modeled stress level is varied, its parameters are updated. The new Alfa can be calculated as follows:

$$Alfa_{i+1} = Alfa_i \times \frac{SL_{i+1}}{SL_i} \quad (3)$$

Notice that the stress level of a machine relates to its state and that of other machines, and the buffer. If buffer and load-sharing situation impress that a machine stress should be increased, then its stress grows up. Sometimes buffer can balance the production rate, thus the stress is not increased.

**3. 2. System Logic Description** System reliability is determined also by the relationship among the components in the system logic configuration. In the system considered in this case study, the upstream stage has a parallel structure and includes four machines where M1&M2 are in series, and M3&M4 are in series. These machines part of a load-sharing structure, and the upstream stage is in series with the buffer and the downstream machine (M5). It is assumed that when the system production outcome is zero, the system is down whereas in the other states, the system is active although at different production levels. Indeed, the production volume depends on the buffer size and downstream stage availability. Also, upstream and downstream machines influence the buffer size. This type of technical dependence is considered in the system modeling.

**3. 3. Cost Modelling** Different formulas have been proposed for maintenance cost modeling [21-23], and several parameters have been considered as direct and indirect costs. In this study, a new formula is proposed that covers new parameters considered for system modeling. In this formula, spare parts cost, replacement cost, preventive maintenance cost, shortage cost (shutdown time), storage room cost and the cost of idle state are considered, and the following equation is derived:

$$TC = \sum_{l=1}^m \sum_{j=1}^n CS_{ij} + \sum_{l=1}^m \sum_{j=1}^n CR_{lj} + \sum_{l=1}^m CPM_l + \sum_{l=1}^m \sum_{q=1}^{s_m} ShC_{l,q} + \sum_{k=1}^h STC_k + \sum_{l=1}^m CI_l \quad (4)$$

In practical industry, the total cost per one product is often used.

$$TCr = TC/V \quad (5)$$

**3. 3. Availability Quantification** Availability defines the ratio of the working time to the total time and is an important parameter to evaluate a manufacturing system, because the production rate depends on system availability. In this study, the Monte Carlo simulation

method is used for system modeling and availability quantification.

Figure 2 shows the framework proposed to determine system availability and cost. Component states, preventive maintenance tasks and RULs are considered to decide on the next ordering, replacement and repair times. In the first step of the method, these times are randomly computed by Monte Carlo simulation for all components and the closest/smallest time is selected. Since, the process that its time is closest should be early conducted.

Depending on the repair type, the repair duration is calculated. Uncertainty in the repair times is defined as a normal distribution and a random variable is sampled to determine the repair duration.

If the stopped machine is one of the upstream stage machines, the series machine is stopped too, whereas the parallel machines continue to work but under higher stress. Thus, the failure rate, RULs and repair times are updated by Equations (2) and (3).

In the repair duration, we deal with two states. In one state, all machines work without failure: this situation is ideal and the system is available. In the other state, one or more machines are stopped. The buffer in this situation is very important for production line stability because if the downstream stage is also stopped, the workpieces produced upstream should be stored in the buffer. In the second situation, the repair times are recomputed and the system state is investigated. If a machine fails, this duration is extended and calculations are repeated so that after the repair duration, all machines are ready to work and available.

After the repair, the new failure times of the components are randomly calculated and the working time is determined. If the desired duration (2000 hr) is greater than T, this cycle is repeated. Also, if the simulation iteration number is less than the number of repeated Monte Carlo runs considered (20000 in this study), the whole procedure is repeated. At the end of the framework, the total cost and system availability are determined. In a nutshell, this framework includes two loops, in the inner loop, C&A are calculated for the desired time (2000 hr) and in the outer cycle this procedure is repeated by 20000 iterations and finally, the average values for A&C are calculated.

In some types of manufacturing systems, since the production rate (at a reasonable cost) is more important than availability, the production volume is also considered. When new times are computed, the production state is checked and if the production rate is increased, stress on active machines is increased to balance the production line, and if production rate is reduced, stress on active machines is decreased. This variation is considered in the machines RULs and maintenance times updating.

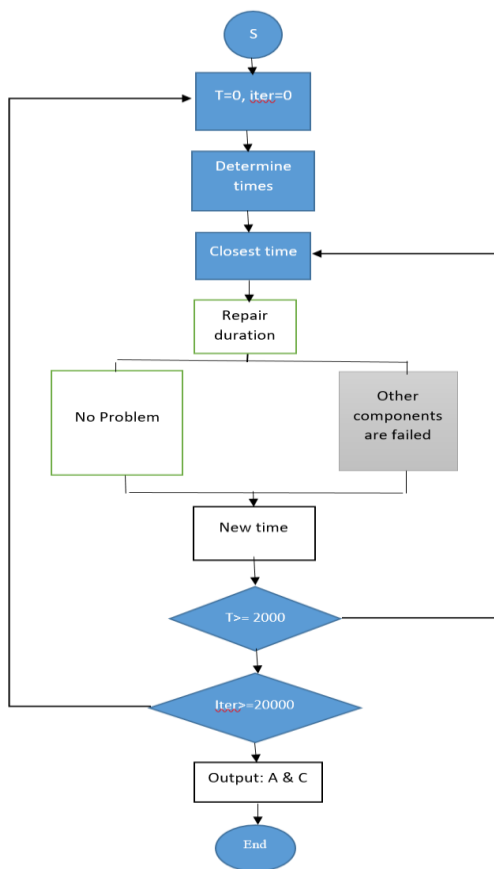


Figure 2. The proposed framework for the system modeling

Other assumptions made in the model include:

- A timetable defines preventive maintenance.
- Spare parts order is carried out when reliability decreases to a specified level.
- Spare parts replacement is performed when reliability is zero.
- Spare parts are provided by a supplier with predefined cost, delivery interval and quality level.
- Preventive maintenance and replacement tasks durations follow normal distributions with given  $(\mu, \sigma)$ .
- When a spare part is replaced, preventive maintenance tasks about this machine is accomplished too.
- The buffer has fixed thresholds of minimum and maximum sizes.
- When M1 is repaired, M2 is stopped and its preventive maintenance tasks are performed too, and vice versa.
- When M3 is repaired, M4 is stopped and its preventive maintenance tasks are performed too, and vice versa.

#### 4. SENSITIVITY ANALYSIS

In this paper, maintenance, spare parts inventory and production planning for smart manufacturing systems are

studied. Different parameters, such as spare parts cost and quality, ordering time, opportunistic maintenance, system logic and buffer size influence the system performance. In this section, these parameters are introduced and their influence is investigated.

**4. 1. System Logic** A manufacturing system layout design is difficult, since different parameters have to be considered. Series or parallel structure is usually utilized for layout planning. The system shown in Figure 1 has a series-parallel structure. Assume the production rate of M1 & M2 is eight components per hour, and M3 & M4 produce ten components per hour, and the production rate for M5 is 18 components per hour. In this situation, the availability of the upstream stage is 0.9038 for 2000 hr working time, and 24904 products are made. On the other hand, downstream availability is 0.8785, and it needs 31622 workpieces. Thus, the downstream has a problem of workpiece shortage, due to the system stop-pages for preventive maintenance. If the load-sharing structure is implemented, when a machine at upstream is stopped, other machines work under higher stress and the production line stability is improved, because the availability of the upstream is raised up to 0.9835 and the number of the total products is 35406. Then, the load-sharing structure helps in production planning and layout design of a manufacturing system, for system performance increase.

**4. 2. Adaptive Production Control** In the past section, the influence of the load-sharing structure on the system performance has been explained. The load-sharing structure increases the upstream production rate. However, the downstream machine cannot consume all workpieces produced, and its production rate needs to be increased. Therefore, another machine in the downstream may be added, which needs more production space and a new cost due to the installation of a new machine; also, the idle time of this stage is increased. As the second plan, we can use adaptive control with feedback to manage this disturbance. When the upstream output production is more than the ordinary capacity of the downstream stage and buffer size, the downstream machine is stressed to increase production; when the workpieces volume in the buffer is not enough, the downstream machine decreases its production rate. Table 1 shows the results of these schemes of implementation.

This Table shows that the system with feedback reduces the machine availability because of stress variation, but the production volume is increased and the system production stability is improved.

**4. 3. Ordering Time** Ordering time is an essential parameter for CBM and spare parts management. The ordering time must be correlated with failure or fault detection times. In industrial practice, spare parts are

**TABLE 1.** System performance with and without feedback

Upstream production volume	Downstream production volume (without feedback)	Downstream availability (without feedback)	Downstream production volume (with feedback)	Downstream availability (with feedback)
35406	31622	0.8785	35385	0.8760

usually ordered when the failure probability is greater than a specified threshold or the reliability is less than a desired value. In this paper, different thresholds are considered and their effect are studied on system availability and cost. Figure 3 shows the correlation between the downstream and upstream availability with different ordering time thresholds.

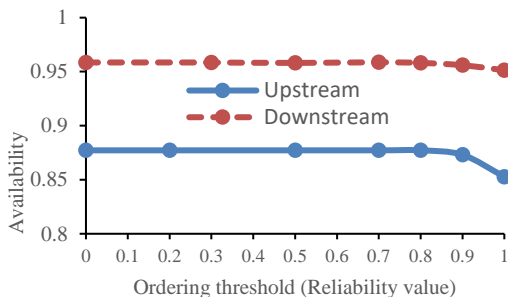
This figure shows that whenever the selected ordering time threshold is close to one, availability is decreased because of shutdowns increase and spare parts shortage. If after the part replacement, the next spare parts are ordered, or in other words, the threshold is close to zero, the availability and production volume are increased, since the probability of spare parts shortage is reduced.

When spare parts are ordered at an incorrect time, the cost is increased because of production stop-page or storage cost increase. Figure 4 shows the relationship between the cost and ordering threshold. The best ordering threshold (reliability value) for the mentioned system is 0.8, and when spare parts ordering is carried out sooner than this time, the cost is increased due to storage cost. If spare parts are ordered with a delay, the cost is increased due to spare parts shortage or system stoppage production.

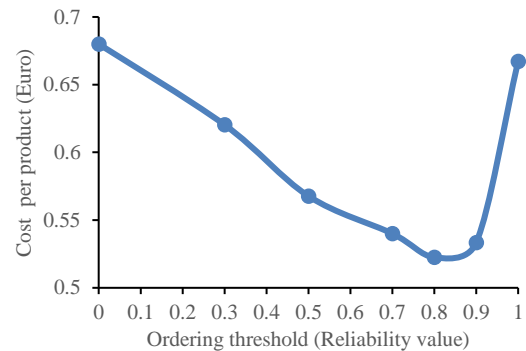
**4. 4. Spare Parts Storage** Storage management is one of the most important parameters for spare parts provision and usually is considered as an indirect cost for maintenance management. A space within the factory is used as storage. This space increases the total cost and when the number of spare parts is increased, storage space needs to be increased too. In this study, the storage cost is considered in the total cost:

$$STC = \sum_{j=1}^m \sum_{i=1}^n time_{ji} \times constant\ cost \tag{6}$$

where  $time_{ji}$  is storage duration for the spare part  $i$  of



**Figure 3.** The influence of ordering time on the availability



**Figure 4.** The influence of ordering time on the cost per component

machine  $j$ , and relates to the ordering time and replacement time.

**4. 5. Opportunistic Maintenance Window**

Opportunistic maintenance is defined as maintenance of an item that is deferred or advanced in time when an unplanned opportunity becomes available [24]. An opportunity arises if the failure of some other parts of a system allows the component in question to be maintained [25]. In this situation, the maintenance opportunity window determination is very important and its size can influence the system cost and availability. Opportunistic maintenance is considered when a machine is stopped for PM or spare parts replacement. In this situation, the desired maintenance is simultaneously accomplished if the opportunity window is greater than the time of the PM tasks. In this study, the opportunity window is selected as an interval between zero and 60 hr for a machine. Figure 5 shows that in the upstream stage, the influence of the opportunity window size on system performance is different from the downstream stage, because of the load-sharing dependence among the components. An opportunity window size increase results in a stress increase on the other components and a system cost increase, because failure probability is raised. In this situation, the load-sharing over-shadows the opportunistic maintenance effect. For the downstream machine, the opportunity window size is important.

Opportunistic maintenance in general decreases system cost, but the cost is increased if the opportunity window is large, because components may be replaced sooner than their expected lifetime.



**4. 6. Buffer Size** Buffer, as a storage between two stages of a production line, stabilizes production line, but it reduces valuable space in a factory and increases production cost. Therefore, in advanced manufacturing system buffer size is kept small. However, if the buffer is omitted, when a machine is out of service in the same production line, other machines should be stopped too. A buffer is usually determined by considering two thresholds of minimum and maximum sizes. Minimum size is significant for production line stability and downstream stop-page reduction due to the workpieces shortage, especially when the amount of the production rate of two stages are the same or the downstream capacity is more than the upstream capacity. Maximum buffer size relates to the production cost and space. In this study, the influence of these thresholds is investigated for two situations: traditional and adaptive control manufacturing.

In a traditional setting, machines work independently of each other, and a large buffer may be necessary. For instance, if the working time is 2000 hours, given the two stages availabilities and production rates (Table 1), the upstream stage produces 3784 workpieces more than the downstream machine capacity as follows.

Production volume of the upstream stage: 35406

Production volume of the downstream stage: 31622

Difference production volume between the two stages=35406-31622=3784

The production rate of the upstream stage= $35406/2000=17.703$  components per hour

The production rate of the downstream stage= $31622/2000=15.811$  components per hour

Thus, for 200 hrs, the production volume of the upstream stage is:

$$P_u = 200 \times 17.703 \cong 3541$$

And the production volume of the downstream stage is:

$$P_D = 200 \times 15.811 \cong 3162$$

Thus,

$$\Delta P = P_u - P_D = 3541 - 3162 = 379.$$

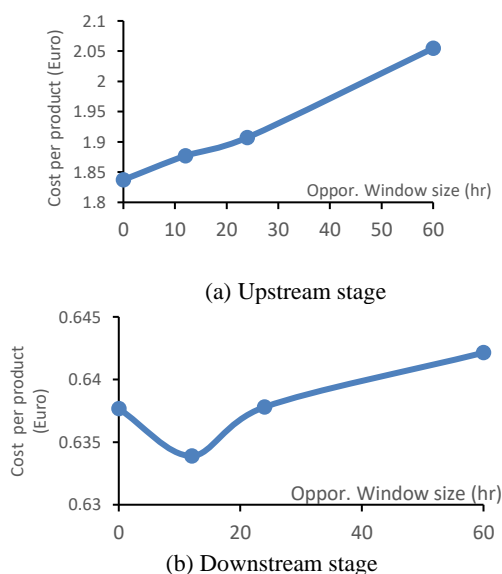
If the buffer size is 380, to reduce the workpieces into the initial state (the buffer is empty), the downstream machine needs more time as follows.:  $time = \frac{379}{15.811} = 23.97 \approx 24 \text{ hr}$

In this duration time, the upstream stage is idle and stopped.

When the adaptive and smart manufacturing system is applied, this problem is reduced, because the downstream machine can increase or decrease its production rate to overcome instability at the upstream output. When the workpiece volume in the buffer is less than the predefined threshold, the downstream production rate is decreased to avoid the workpiece shortage, and when the buffer is filled, its production rate is increased. In the proposed technique, all outputs of the upstream stage are used by the downstream machine and production stop-page is decreased. Also, the required buffer size is reduced. In this state, given the buffer size, at the end of working time and in the worst case, the buffer is full.

In this study, different values for buffer thresholds are considered (Figure 6). To compare the effect of different buffer thresholds on the system, a threshold is used as a reference and the other results are normalized. Figure 6a shows the influence of the maximum buffer size on the system performance. System capability to absorb production line fluctuation is increased with larger buffer size. Then, stress on the machines is reduced; consequently, system availability is increased and the cost per part is reduced. For a large threshold, this influence can be neglected.

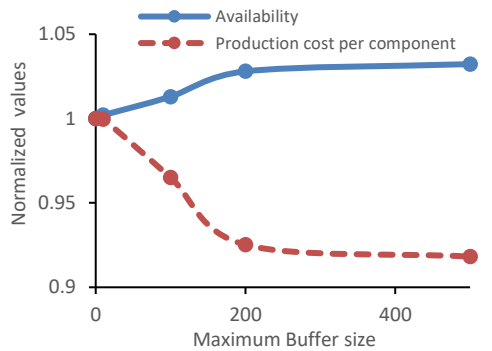
Figure 6 (b) illustrates the minimum buffer size influence on the system performance. When this threshold has small values, the stress on the downstream machine is decreased; and it is increased for large values. The threshold effect on the upstream machine is opposite. The influence of the maximum buffer size on the system performance is more significant than that of the minimum buffer size.



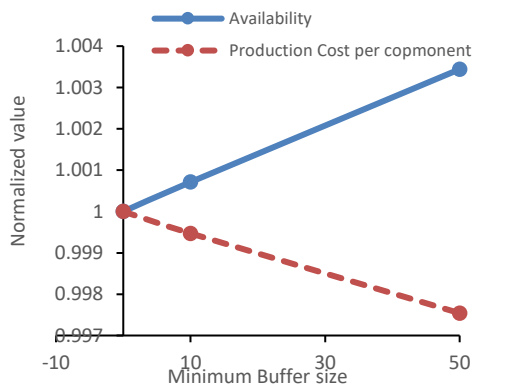
**Figure 5.** The influence of the opportunity window size on the cost

#### 4. 7. Production Rate Ratio

The ratio of the production rate between machines is one of the main parameters considered for production line design. For design, the production rate for downstream and upstream is taken equal; but when maintenance and spare part inventory are jointly considered with production planning, the problem becomes complicated and it is necessary to find the optimal ratio between the downstream and upstream stages for production line balance.



(a) Maximum buffer size effect (minimum size=0)



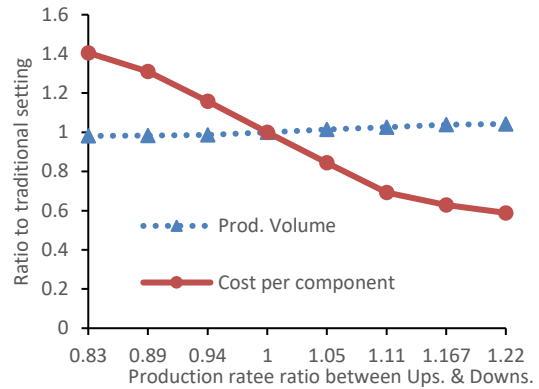
(b) Minimum buffer size effect (maximum size=100)

**Figure 6.** Buffer size effect on the system

To study the influence of this parameter on the system performance, it is assumed that the downstream machine production rate can be varied from 0.83 to 1.22 times the upstream production rate. Figure 7 shows the production rate ratio effect on the cost per component and production volume for the system with adaptive control. These data are normalized and it is assumed that the upstream production volume is constant.

When the downstream production capacity is higher than the upstream capacity, the production volume of the downstream is greater than upstream, and sometimes it may be idle. Then, the downstream production rate should be decreased and the stress on its machines is also reduced. Consequently, the probability of failure and the cost per component is reduced. When the downstream capacity is less than the upstream, it works under higher stress; then, the probability of failure is increased and the total cost is increased too. Thanks to the adaptive control utilized in the system, the production volume is approximately constant and small variations in availability are generated by the delay in the adaptation process.

If the adaptive control is not utilized, in the extreme case that the downstream machine capacity is 1.11 times the upstream production, the production line stability is acceptable. In this state, in one percent of the working



**Figure 7.** Production rate ratio effect

time, the downstream machine is idle due to the workpieces shortage, and in 2.5 percent of the working time, it faces an extra production from the upstream stage. These results show that if adaptive production control is not applied, the production line stability is decreased and the effectiveness of the buffer, maintenance and spare parts management is reduced.

## 5. CONCLUSION

Smart manufacturing systems are the next industrial revolution. For increased functionalities, benefits and efficiency, they involve complex structures with different dependencies, including structural, stochastic, economic and source dependencies. System complexity is increased due to the integration of supporting systems, such as maintenance, spare parts inventory, and buffer allocation.

In this paper, smart manufacturing systems with series-parallel structure which involve load-sharing, functional and economic dependencies are considered. Actually, smart systems with adaptive control and feedback are considered to improve system performance, production stability and the effectiveness of maintenance. The results show that the resilience and dynamic behavior of smart systems increases the systems adaptation to working conditions. The role of the buffer as a balancer in production lines to improve availability is very important and the optimum size of the buffer should be selected. Ordering time and replace time of spare parts depend on reliability and they can impress availability and the cost of the system. Opportunistic maintenance is a good idea, but its influence on availability depends on the machine's location on the production line. In the future studies, resource dependence, multi-state configuration, corrective maintenance policy, imperfect maintenance, customers' requirement variability, and spare parts quality variability will be considered.



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## Persian Abstract

## چکیده

سیستم های هوشمند تولید بخشی از انقلاب صنعتی جدید هستند که نیازمند پاسخگویی برخط به نیازها و تغییرات ایجاد شده در سیستم هستند. در این سیستم ها انواع مختلف وابستگی برای بهبود راندمان استفاده می شود، وابستگی های از نوع ساختاری، استوکستیک، فنی و اقتصادی. سیستم های پشتیبان این نوع از خطوط تولید نیز دارای مرزهای مشترک و وابستگی هستند. در این مقاله نقش دیسیپلین تعمیر و نگهداری، تدارکات و پشتیبانی قطعات مصرفی و اندازه بافر در این خطوط تولید مورد بررسی قرار گرفته است. وظیفه مشترک و وابستگی ماشین ها در انجام ماموریت همراه با سیستم کنترل تطبیقی تولید و وابستگی اقتصادی بطور ویژه بررسی شده و اثر آنها بر میزان تولید و دسترس پذیری سیستم بوسیله روش مونت کارلو مدلسازی شده است. نتایج بیانگر این نکته است که هرچند طراحی این سیستم ها پیچیده بوده و وابستگی بین اجزای سیستم افزایش می یابد، اما میزان دسترس پذیری و حجم تولید نهایی افزایش یافته و با ارتقاء راندمان هزینه کل کاهش می یابد.