A methodology for estimating the operating costs of production lines

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Abstract: The paper proposes a methodology for the cost assessment of production lines with unreliable machines and finite buffers. This methodology is based on the new concept of "Line Equipment Cost" (LEC), that is the actual operating cost of a certain machine which is used into a certain line configuration. For each machine, this kind of cost not only depends on a set of static parameters describing the statistical and structural properties of the machine, but also on its actual performance which, in turn, strictly depends on the specific line configuration where the machine is installed. If the line configuration is modified (e.g., more/less buffer space is available) the machine's performance is expected to improve/degrade so that its LEC value, which dynamically expresses the machine's actual operating cost, must be properly adjusted. Hence, in order to evaluate any production line, first the specific LEC values of the single machines in that line should be computed, then the "Total Line Cost" (TLC) can be determined by summing up those LEC values. Finally, the paper provides some numerical results in order to show the applicability of the proposed methodology which can be used not only to evaluate the actual operating cost of a specific production line (expressed by the TLC value), but also to compare different line configurations in order to drive strategic decision.

Keywords: production lines; operating costs; unreliable machines.

1.Introduction

A production line is generally defined as a manufacturing process, usually adopted in case of high-volume flow production, where machines and other devices (e.g., buffers) are laid-out according to the processing sequence of the products. Since machines and buffers are unreliable and capacitated, the performance of any production line is strongly influenced by (i) the intrinsic uncertainty related to failures and other flow disruptions, and (ii) the cross-interaction between machines and buffers (i.e., "blocking" and "starvation" phenomena may occur as failures or other flow disruptions propagate along the line, in the upstream and downstream of the line respectively). Thus, it is the disruptive effects of randomness on one hand and machine-machine interaction on the other hand that give rise to the need for stochastic approaches in order to estimate the actual line performance, whether expressed as *production performance* (e.g., line production rate and line efficiency) or *cost performance*.

The interesting point is that while the analysis of what we call *production performance* has long attracted the interest of researchers concerned with both analytical and simulation modelling, at the best of authors' knowledge there are very few theoretical results about the estimation of the *cost performance* of production lines in stochastic environments. This is the interesting consideration that motivated the present paper which aims at assessing the operating costs of production lines (i.e. of all machines and buffers constituting that line) by taking into account the actual consumption of resources.

Although focused on the context of flow manufacturing, the objective of this study reflects the more general need for organizations operating in various sectors to overcome some of the limitations of traditional cost accounting in order to have more accurate cost information. This is in accordance with the growing popularity of accounting techniques such as activity-based costing (ABC). Since its introduction by Kaplan and Cooper (Cooper and Kaplan, 1988) there have been several applications of the ABC method in both manufacturing and services, and across the whole spectrum of company functions (see, e.g., Gupta and Galloway, 2003). The basic principle of the ABC method of accounting is to breakdown the system into individual activities, compute the cost of these activities and then assign the costs to the cost-objects based on the consumption of activities. For the sake of this study, it is of particular interest the work by Spedding and Sun (1999) in which activity based costing is included into the discrete event simulation model of a semi-automated assembly line with the aim of realising an on-line costing mechanism. Nevertheless, the authors of this research recognized that the verification and validation phase of the simulation model is negatively affected by the introduction of additional information such as cost information. Moreover, simulation time increases considerably, thus emphasizing the need for an efficient tool able to estimate the actual *cost performance* of a manufacturing system.

Similarly to the ABC approach which assigns overhead costs to the activities according to the actual consumption of resources, the approach presented in this paper assigns the line operating costs to the different devices installed in that line (machines and buffers) according to their actual *production performance*. It can be noted that, while in a typical ABC approach the activities and the corresponding cost-drivers can be independent of one another, in this case the basic cost-driver is the line *production performance* which strictly depends on the way machines and buffers interact along the line. This means that any change on any machine/buffer (i.e., the line configuration changes) may affect the cost allocation on all the other machines and buffers of the line. Moreover, by making use of stochastic approaches provided by the literature on production line modelling, this study shows an interesting application where the cost-driver is not a deterministic factor, as usually is in traditional ABC approaches, but takes into account stochastic phenomena. Finally, as shown in the case study described in Section 4, the proposed cost assessment methodology is not only useful for obtaining more reliable product costs, but may help managers and practitioners in assuming strategic decisions about the configuration of the production line under analysis.

The remainder of the paper is outlined as follows. The problem statement is presented in Section 2. The cost assessment methodology is described in Section 3. Some numerical results are provided in Section 4. Finally Section 5 draws some conclusions.

2.Problem statement

The problem addressed in this paper is to estimate accurate cost information of production lines consisting of unreliable machines and finite buffers, by assuming a single-product setting. Specifically, a cost assessment methodology is proposed to assign operating costs through the machines/buffers to the products, according to the actual *production performance* of the line.

In the following, a simple but explanatory example is presented in order to clarify the problem statement. Consider a machine A with a nominal capacity of 100 items/[prod hours] installed in two different lines, line L1 and line L2 (Figure 1). A preventive maintenance contract exists between the manufacturer/distributor of machine A and the company where the machine is installed so that the estimated cost is 50 €/[100 prod hours].

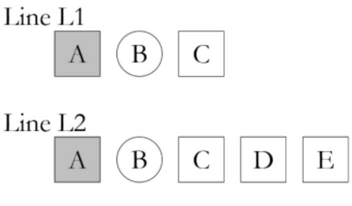


Figure 1: Explanatory example.

Since line L2 has two more stages than line L1 and all the stages are unreliable, we expect that the actual production rate of L2 will be lower than that of L1, and both lower than the nominal capacity of machine A. Suppose that the production rate **P** of both lines has been estimated and that, e.g., **P**(L1) = 980 items/h and **P**(L2)= 890 items/h. Let us assume now that both lines must produce 1000 items. The actual cost for the "maintenance service" of machine A will be different in the two lines even if the total amount of production is the same. Specifically, the cost of machine A will be 51 €/[1000 items] in the case it is installed in L1 and 56 €/[1000 items] in the case it is installed in L2. Thus, the two different installations of the same machine differ of about 10% with respect to the same cost component. The same reasoning can be applied to all the machines and buffers in any line, thus emphasizing the need to relate the *cost performance* to the corresponding *production performance* as occurs in the innovate cost assessment methodology proposed in the sequel.

3.Cost Assessment Methodology

The proposed methodology for computing the actual operating cost of a production line, that is its *cost performance*, is depicted in Figure 2. In the following, it is assumed that each equipment constituting the line under analysis can be either a machine or a buffer, where a machine is any device which processes operations on the products and a buffer is any storage device which receives and releases the products without performing value-added operations.

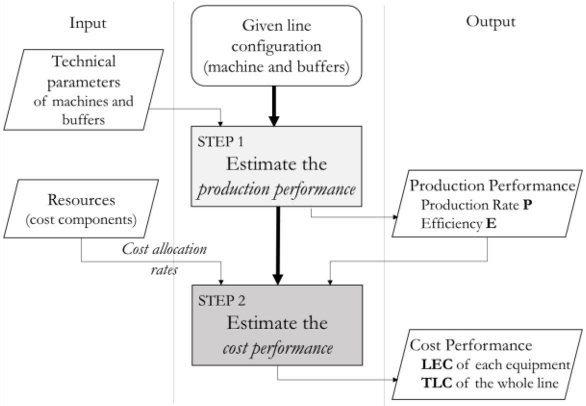


Figure 2: Cost assessment methodology.

For a given line configuration, the first step is to estimate the actual *production performance* in terms of production rate **P** and efficiency **E** of the line. A brief discussion about analytical and simulation approaches for studying the stochastic behaviour of a production line is provided in Section 3.1. For the sake of this study, it is assumed that a proper analytic/simulation model is always available in the literature so that, given a certain line configuration and a number of technical input parameters of each equipment (e.g., machine nominal capacity or buffer size, probability distribution of time-to-failure, probability distribution of time-to-repair), the *production performance* of the line can be estimated in a stochastic domain.

The second step is the core step of the proposed methodology, as described in details in Section 3.2. The *cost performance* is computed by taking as input both the actual *production performance* (which is the output of the previous step) and some cost allocation rates which are linked to the resources that each equipment of the line consumes. Hence, the new concept of "Line Equipment Cost" (**LEC**) is presented. As depicted in Figure 3, the LEC is computed for each equipment of the line by assigning the resources (or cost components) according to both the equipment's cost allocation rates (depending on the specific machine/buffer taken into consideration) and the overall *production performance* (depending on the production line as a whole). As a result, the LEC value is the operating cost of a certain equipment which is installed in a certain production line, and it may be expected to vary if the same equipment is installed in different line configurations.

Finally, once the LEC values have been computed for each equipment of a certain production line, we can find the "Total Line Cost" (**TLC**) as the actual operating cost of that specific line configuration, as described in the sequel.

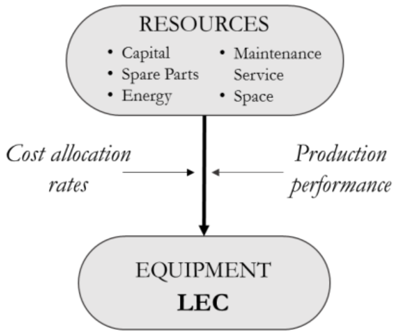


Figure 3: Line Equipment Cost.

3.1 STEP 1: Line Production Performance

The first step of the proposed methodology is to estimate the *production performance* of the production line under analysis. For this purpose, the most popular approaches can be classified in analytical methods and simulation methods.

As regards the first category, an extensive body of literature is devoted to the modelling of production lines with Markovian machines and finite buffers (that are especially suited to automated lines where human intervention is least evident). For reasons of mathematical tractability, exact analytical models are available for short lines only. These short lines, usually called "building blocks", are made up of two Markovian machines decoupled by a finite buffer. Since the first contributions during the 1960s, more and more accurate and sophisticated models of building blocks have been developed, e.g., in order to include different failure modes and general Markovian machines (see, e.g., Colledani an Tolio, 2011, Tan and Gershwin, 2009) or different control policies (see, e.g., the work by Gebennini et al., 2015, that is applied in Section 4). Although it might seem a simple case, the study of building blocks is crucial for line performance analysis since it is the basis for approximated techniques which allow the assessment of longer and more complex manufacturing systems (see, e.g., the decomposition technique proposed in Maggio et al., 2009). Hence, the analytical modelling of production lines is not only of theoretical interest, but also of practical significance.

As regards the second category, an interesting review about simulation applications has been given by Jahangirian et al. (2010). According to this study the simulation techniques which recently showed the highest growth rate are discrete event simulation (DES), system dynamics (SD), agent-based simulation (ABS) and simulation gaming (SG). Among them, DES remains the most popular technique used in manufacturing. The reader may refer to surveys such as Smith (2003), and works such as Padhi et al. (2013) for interesting applications to the analysis of production lines. In general, simulation is a highly effective tool for the design of manufacturing systems given its flexibility and ability to model real-world complexity. As an example, time-to-failure or time-to-repair can be modelled by means of whatever statistical distribution, and a finer level of detail could be included, if needed, in the system description. Hence, simulation models require fewer simplifying assumptions than analytical models, thus enabling complex, large, and real-world problem to be treated. On the other hand, while analytical models describes mathematically the operating characteristics of the system, simulation models do not allow a deep understanding of the system's behaviour since the relationships between the design parameters and the resulting performance measures are not explicitly known. As a consequence simulation may lead to high computing costs due to the amount of time that has to be spent both in the definition of the model and/or "metamodels" (which often results in a trial-and-error process) and in the achievement of satisfactory and statistically relevant performance measures. To sum up, analytical modelling and simulation have different and complementary advantages and limitations so that the selection of the most suitable approach depends on such issues as the complexity of the system to be modelled, the amount of information that needs to be provided by the model, the expected level of detail, the computational effort for generating, implementing and validating the model, and so forth.

3.2 STEP 2: Line Cost Performance

The second step of the methodology allows to compute the "Total Line Cost" (TLC), that is an accurate estimate of the cost for operating and managing a given production line (i.e., the *cost performance*).

The idea is to consider each machine and buffer installed in the line and estimate the corresponding LEC value which expresses the cost for operating that specific machine/buffer in that specific line. Then, the TLC of the whole line simply results to be the sum of the different LEC values. Thus, if the production line is made up of *n* devices (machines or buffers), we have:

$$\mathrm{TLC} = \sum_{i=1}^{n} \mathrm{LEC}_i \qquad (1)$$

In the sequel, the new concept of LEC value is described in detail.

2.2.1 Line Equipment Cost (LEC)

For each machine/buffer operating in a certain production line, the "Line Equipment Cost" (LEC) is the actual operating cost which depends on:

- the features of the very machine/buffer (i.e., the cost allocation rates), but also
- the specific line configuration where the machine/buffer is installed and the way it

interacts with other devices (i.e., the line *production performance*).

In order to determine the LEC value, it is necessary to identify the consumed resources (i.e., the cost components) and the corresponding cost allocation rates which are deterministic factors depending on the specific equipment under analysis. Then, the line *production performance* is used here as the basic cost-driver for assigning the operating cost through the equipment to the products.

By generalizing the results obtained through a collaboration with an important company operating in the packaging industry, the following resources and cost allocation rates have been identified for a generic equipment installed in a production line (for the sake of simplicity the euro is used here as the reference currency):

- Capital: the cost allocation rate for this resource is called here *capital factor*, which expresses the estimated costs of purchasing and maintaining the equipment on a certain allocation base, which is here supposed to be the production time. Hence, the capital factor (expressed, e.g., in [€/prod hours]) can be computed as:

  $$F_{\text{cap}} = \frac{P}{H_{\text{year}}\, T_{\text{d}}},$$

  where P is the purchase price of the capital equipment; H_{year} is the expected number of production hours per year (estimated by the plant management); T_{d} is the depreciation life in years.

- Spare-Parts: the cost allocation rate for this resource is called here *spare-parts factor*, which expresses the estimated costs for spare parts after a certain production time or production quantity. It is generally provided by the manufacturer/distributor of the equipment. In the sequel, the spare-parts factor is denoted as F_{spare} and it is assumed to be expressed in terms of money for a production quantity of Y items, i.e. [€/(Y items)].

- Maintenance Service: the cost allocation rate for this resource is called here *maintenance factor*, which expresses the estimated costs for preventive maintenance on a certain allocation base, which is here supposed to be the production time. It can be noted that this kind of cost allocation rate can be easily computed if, as often occurs in case of automated flow lines, there exist a preventive maintenance contract between the distributor and owner of the equipment. Specifically, it can be expressed as:

  $$F_{\text{maint}} = h_{\text{maint}}\, c_{\text{man}}\,,$$

  where h_{maint} is the expected number of man-hours required for the "preventive maintenance service" after a certain amount X of production hours (generally provided by the manufacturer/distributor of the equipment); c_{man} is the hourly labour cost. Hence, the unit of measurement for this cost allocation rate results to be [€/(X prod hours)].

- Energy: since the same equipment consumes a different amount of energy according to its operational state, two (or even more) cost allocation rates can be identified. Specifically, the e*nergy-production factor* expresses here the hourly energy cost when the machine is in the "production" state. It can be expressed as:

  $$F_{\text{en-prod}} = e_{\text{en-prod}}\, c_{\text{en}}\,,$$

  where $e_{\text{en-prod}}$ is the energy consumption [kW] when the machine is in the "production" state; c_{en} is the cost of energy in the local market [€/kWh]. Conversely, the *energy-idle factor* expresses here the hourly energy cost when the machine is not producing. It can be expressed as:

  $$F_{\text{en-idle}} = e_{\text{en-idle}}\, c_{\text{en}}\,,$$

  where $e_{\text{en-idle}}$ is the energy consumption [kW] when the machine idle; c_{en} is the cost of energy in the local market [€/kWh] as above.

- Space: the cost allocation rate for this resource is called here *footprint factor*, which expresses the estimated costs for space occupation on a certain allocation base, which is here supposed to be the production time. It can be expressed as:

  $$F_{\text{foot}} = c_{\text{foot}} \frac{W\, L}{H_{\text{year}}},$$

  where W and L are the physical dimensions of the equipment (i.e., the equipment width [m] and length [m], respectively); H_{year} is the expected number of production hours per year (estimated by the plant management); c_{foot} is the annual rental rate in the local market [€/(mq·year)].

Once the cost allocation rates discussed above have been computed for the specific equipment under analysis, the line production rate **P** and efficiency **E**, estimated according to one the approaches of Section 3.1, are used to assign the different cost components. Specifically, the analytical expression of each cost component is as follows:

- "Capital Cost"

  $$C_1 = \frac{F_{\text{cap}}}{\boldsymbol{P}}\,,$$

- "Spare Part Cost"

  $$C_2 = \boldsymbol{E} \cdot F_{\text{spare}}\, Y\,,$$

  where Y is the allocation base used in the spare-parts factor as discussed above,

- "Preventive Maintenance Cost"

  $$C_3 = \frac{F_{\text{maint}}\, X}{\boldsymbol{P}}\,,$$

  where X is the allocation base used in the maintenance factor as discussed above,

- "Energy Cost"

$$C_4 = \frac{\left[\boldsymbol{E} \cdot F_{\text{en}}^{\text{prod}} + (1 - \boldsymbol{E}) \cdot F_{\text{en}}^{\text{idle}}\right]}{\boldsymbol{P}},$$

- "Footprint Cost"

$$C_5 = \frac{F_{\text{foot}}}{\boldsymbol{P}}.$$

Hence, for each machine/buffer *i* in the line we find the corresponding LEC value as:

$$\text{LEC}_i = \sum_{j=1}^{5} C_j \qquad (2)$$

Finally, the TCL of the whole production line is computed according to Eq. (1).

4.Numerical Results

In this section we discuss some numerical results by considering a short line, commonly called "building block", made up of two machines decoupled by a finite buffer (see Figure 4). The line under analysis is controlled by a specific policy that is usually adopted when the first machine is the most critical machine of the line, as often occurs in, e.g., the food and beverage sector. According to this policy, each time the first machine becomes blocked (i.e., the buffer is full) it is prevented from resuming production until the buffer becomes empty again.

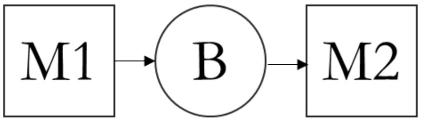


Figure 4: Building block.

The technical parameters of the machines and the buffer are the input data as shown in Table 1.

Table 1: Input data: technical parameters

Parameter	M1	Buffer	M2
MTTR [hh:mm:ss]	00:07:15	00:02:30	00:02:30
MTBF [hh:mm:ss]	01:30:00	15:00:00	00:30:00
Machine Speed (nominal) [items/prod hour]	10 000	-	12 000
Buffer Size [items]	-	500	-

Hence, the line *production performance* can be estimated by taking stochastic phenomena (i.e., failures and repairs in this case) into consideration. Specifically, the Markov model described in Gebennini et al. (2015) has been applied, thus obtaining the following results:

P = 8 919 items/prod hour,

E = 89.2%,

where the line efficiency **E** has been computed by relating the actual production rate of the line **P** to the nominal capacity of the first machine (i.e., the slowest machine). It can be noted that the same results can be obtained by simulating the line with any DES tool with a sufficiently long run-time to reach the steady-state condition.

Then, in order to estimate the *cost performance* according to Section 3.2, the LEC of each machine/buffer is computed by considering both the *production performance* computed above and the cost allocation rates. The allocation rates are shown in Table 2.

Table 2: Input data: cost allocation rates

Parameter		M1	Buffer	M2
Capital Factor [€/prod hour]	F_{cap}	12.50	3.50	7.50
Spare-Parts Factor [€/(1000 items)]	F_{spare}	0.25	0.07	0.15
Maintenance Factor [€/prod hour]	F_{maint}	1.50	0.75	1.00
Energy-production Factor [€/prod hour]	$F_{\text{en-prod}}$	5.00	3.20	5.00
Energy-idle Factor [€/prod hour]	$F_{\text{en-idle}}$	2.00	1.00	1.00
Footprint Factor [€/prod hour]	F_{foot}	0.75	0.43	0.23

The resulting LEC values of the two machines and the buffer, expressed in terms of euros per 1000 produced items, are reported in Table 3 along with the decomposition in the five cost components.

Table 3: Output data: LEC values

Parameter		M1	Buffer	M2
LEC [€/1000 items]		**2.401**	**0.919**	**1.625**
Purchase Cost	C_1	1.402	0.392	0.841
Spare-Part Cost	C_2	0.223	0.062	0.134
Preventive Maintenance Cost	C_3	0.168	0.084	0.112
Energy Cost	C_4	0.524	0.332	0.512
Footprint Cost	C_5	0.084	0.048	0.026

Finally, by summing up the LEC values (see Eq. 1) we obtain the TLC of the whole line:

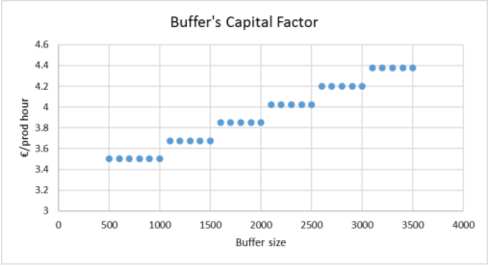
TLC = 4.945 €/1000 items.

This is the cost for operating the specific line under analysis, excluding the cost of raw/packaging material (thus, independent on the value of the items that are produced) and the labor cost of the workers employed in the system.

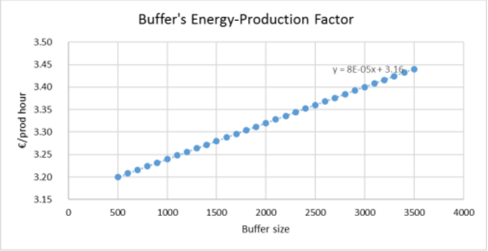
It is interesting now to evaluate how the TLC varies as the line configuration changes. As an example, suppose that the problem is to find the best size of the intermediate buffer in order to minimize the TLC of the line. Hence, the technical parameter "buffer size" is allowed to vary within a range of possible values which, in this case, is from 500 items to 3500 items. As the buffer size increases we expect that two contrasting effects take place, thus motivating the investigation of a trade-off. Specifically, as the buffer size increases, we have:

- POSITIVE effect: the line *production performance* improves because the decoupling level between the two machines increases with the buffer size;
- NEGATIVE effect: all or some cost allocation rates (e.g., the buffer's capital factor, the buffer's spare-part factor, etc.) increase because a different type of equipment and/or more components are needed as the buffer size increases.

As regards this second effect, first we need to identify the cost components (or resources) which are affected by the buffer size (that, in this case, is the only variable which identifies different line configurations). Then, the functions describing how the cost allocation rates vary with the buffer size have to be found. In this specific case study, it is assumed that the cost allocation rates of the buffer increase with its size. Specifically, we adopted a step function for the buffer's capital factor as depicted in Figure 5 a), while the remaining cost allocation rates of the buffer increase with its size in a linear manner. As an example, the function of the energy-production factor is shown in Figure 5 b), where a fixed percentage increment of 0.25% is applied each time the buffer size increases by 100 items. On the other hand, since the machines does not change, their cost allocation rates remain constant.



a)



b)

Figure 5: Capital Factor and Energy-Production Factor of the buffer as a function of the buffer size

At this point, the methodology proposed in this paper can be iteratively applied for different values of the buffer size. As discussed in the sequel, the results are not trivial because the cost assignment process depend on both the cost allocation rates and the actual *production performance*.

The production performance, still computed according to Gebennini et al. (2015) or through a simulation campaign, is shown in Figure 6 in terms of actual production rate of the line **P** and line efficiency **E**. Then, the LEC values of the two machines and the buffer can be computed and, finally, the TLC values are determined for the corresponding line configurations.

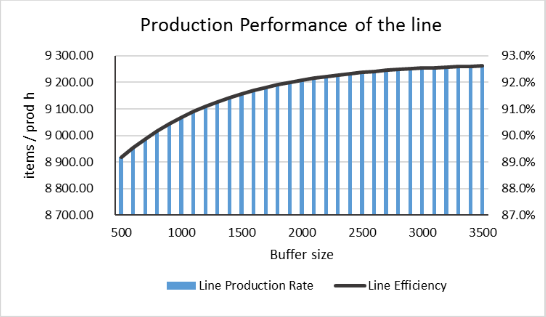


Figure 6: Production performance for different buffer sizes.

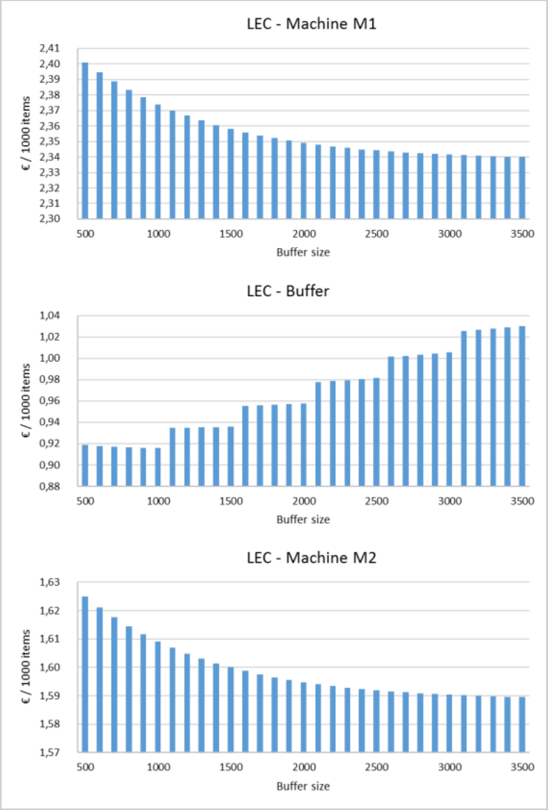


Figure 7: LEC values for different buffer sizes.

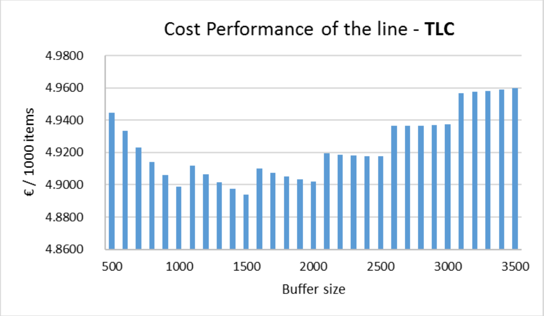


Figure 8: TLC values for different buffer sizes.

As regards the LEC values of the two machines (Figure 7), they are both decreasing with the buffer size. This is as expected, because while the cost allocation rates are constant, the production performance improves. On the other hand, the LEC value of the buffer is increasing with its size, meaning that for this particular equipment the improvement in the production performance is not enough to counterbalance the increase of the cost allocation rates. Moreover, since the capital factor has a great impact, the trend of the LEC of the buffer shows the influence of the step-function of Figure 5 a). Considering now the production line as a whole, the TLC of each configuration is computed by summing up the LEC values of the machines and the buffer for the same line configuration. The interesting result, depicted in Figure 8, is a decreasing-increasing function which shows that, although the cost allocation factors of the buffer increase, such negative effect can be counterbalanced by improvements in the line *production performance* for a significant range of values of the buffer size. Specifically, the minimum TLC is for a buffer size of 1500 items, which corresponds to the largest buffer in the second step of the cost function of Figure 5 a). This solution is anything but trivial since the line configuration correlated to the minimum TLC is not the one with the cheapest buffer. Even more surprising is that line configurations with larger and more expensive buffers (up to 2500 items in this case) are better, in terms of operating cost per 1000 produced items, than line configuration with small buffers (800 items or less).

Hence, by identifying a non-trivial set of line configurations with the least TLC values, these results emphasize the need to relate the *cost performance* of a production line to its actual *production performance*. This is not only important for the cost assessment of a given production line, but for allowing managers to base strategic decisions on more accurate information.

5. Conclusions and Further Research

The paper proposes a methodology for estimating the actual operating costs of production lines with unreliable machines and finite buffers. The motivation arises from the observation that the same equipment installed in different line configurations may give rise to different operating costs. Hence, we introduced the new concept of "Line Equipment Costs" (LEC) which is the actual cost for operating a specific equipment installed in a specific production line. In particular, the LEC of a given equipment depends not only on a set of deterministic cost allocation rates (which depend on the type of equipment), but also on the *production performance* of the line where the equipment is installed (which, in turn, is affected by randomness and machine-machine interactions). As a result, the same equipment installed in different line configurations may have different LEC values. Finally, given a certain line configuration, the "Total Line Cost" (TLC) can be determined as the sum of the LEC values of the installed devices.

As shown in the proposed numerical example, the notions of LEC and TLC allow to relate the *cost performance* of a production line to its actual *production performance* (i.e., to the actual consumption of resources) by providing more accurate cost information which is not only useful for assessing a given production line but also for driving strategic decisions. Specifically, in the case study proposed in this paper the TLC values have been computed for production lines with different buffers in order to select the buffer size which is more convenient in terms of operating costs. The interesting result is that the buffer size which leads to the least TLC is not that of the cheapest buffer, but the buffer size which allows an improvement in the line *production performance* that counterbalances the increased cost allocation rates.

Further research should be carried out toward including new cost components in the cost assessment methodology. For example, the resource pool evaluated to compute the LEC value of a certain equipment can be extended to consider the labor cost of the workers employed in the system. This extension could be especially useful in case of assembly and or semi-automated lines with manual intervention. Finally, the applicability of the methodology to real-world problems in different industry sectors should be examined in future works.

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