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International Journal of Engineering Business Management
Special Issue on Innovations in Fashion Industry

Bucket Brigades to Increase Productivity in a Luxury Assembly Line

Regular Paper

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Received 1 June 2013; Accepted 15 July 2013

DOI: 10.5772/56837

Abstract One of the most challenging issues in manual assembly lines is to achieve the best balance of workloads. There are many analytic approaches to solve this problem, but they are often neglected, since they are time-consuming and require high level engineering skills. Fashion bags packaging lines must comply with a number of different products with low production volumes, while the organization of the line is often under the mere responsibility of the foreman, who balances workloads in an empirical way. The aim of this work is to evaluate the effectiveness of the arrangement of bucket brigades (BBs) for an assembly line of luxury handbags. To do this, it was decided to perform a testing activity in a company producing fashion handbags in order to compare the self-made design with the BBs and with a simple assembly line balancing problem algorithm. The originality of this research lies in the fact that there are no studies in the literature on BBs applied to the packaging of highly variable small batches. The results were excellent, showing the advantages of BBs in terms of flexibility, the reduction of work in the process and the ability to handle small anomalies.

Keywords Bucket Brigades, Assembly Line, Production Optimization, Handbag Packaging

1. Introduction

A classic challenge in the management of assembly production is the balancing of the line [1], meaning finding an optimal partition of the total amount of work into a certain number of well-defined tasks that later have to be assigned to stations. In operations management, this recurring and important decision problem is known as the ‘Assembly Line Balancing Problem’ (ALBP) [2], and it must be solved any time an assembly line has to be configured or reconfigured [3]. A less general formulation of the same problem is the ‘Simple Assembly Line Balancing Problem’ (SALBP) [4] [5]: this is easier to solve because it is regulated by certain assumptions that are very restricting and simplifying with respect to real cases of assembly lines. Several versions of the SALBP arise by changing the objective function, and the literature offers a large variety of solving approaches for this kind of problem: exact optimization methods, heuristic methods and artificial intelligence techniques. However, traditional means of organizing a production line, such as the classical assembly line, are inflexible because workers are assigned fixed work stations and the station with the greater work content dictates the rhythm of the line, becoming a bottleneck [6]. In an industrial context where flexibility gains more and more importance, a variation of the classical assembly line has recently been introduced to abolish the rigid assignment of work: it is a new way of organizing work called 'Bucket Brigades' [7]. This arrangement may find this original intuition in the observation of some natural organizations [8] [9] [10].

The BBs perfectly fits into labour-constrained systems, in which cross-trained workers perform multiple tasks or tend more than one workstation; in these lines, there are more machines than workers and so labour becomes the key constraint in the system, which exhibits the more complex behaviour of simple lines because the flow of work is affected by the number and characteristics of both machines and workers [11].

The solution of the BBs proposes a dynamic partition of the work content between workers so that the system is governed by some typical rules that ensure the self-balancing of the line; moreover, this line can be thought of as a constant work in process (CONWIP) line [12], with the work in process (WIP) level equal to the number of workers (actually, it never exceeds this number) [13].

The property of self-balancing avoids the difficulty of solving the classical and far more complex ALB problem: the cycle time (CT) - which is the most frequently used optimization objective in the ALB approach - is implicitly minimized. From the practical perspective, many implementations of BBs lines demonstrate two major beneficial effects, namely the increase of the production rate (or throughput rate - TR) and the reduction of the WIP; furthermore, the design and supervision effort of the management is surely reduced [14].

A production line in which there are more stations than workers can be arranged according to the BBs production model. In this paradigm, every worker brings a single piece from station to station. Since workers are not allowed to pass each other, if the next station is occupied, the worker waits for that station to become available. Every time that the last worker completes an item, he moves back to take possession of the item of his predecessor. The latter leaves it and walks back to get the item of his predecessor, and so on until the first begins a new article.

BBs have found their main appreciation in apparel manufacturing, assembly lines [15], distribution warehousing [16], and maintenance management [17] [18]. In most applications, groups are formed by two or three workers [19].

Increased international competition and growing economic importance have caused, in recent years, the growing attention of researchers in the fashion field, where problems and solutions have become closer to those of more mature industries. The topics dealt with by the researchers look for methods to enhance logistical innovation and integration [20] [21] as well as tools to perform effective performance measurement [22], proper layout selection [23], the appraisal of the brand equity [24] and suitable adaptations of forecasting techniques [25] [26].

The fashion industry and, in particular, the packaging lines of luxury products, are an area in which the BBs methodology could be remarkably suitable. No particular attention has been paid by researchers to investigating the performance of BBs in such an area, where high variability and low volumes are involved. A continuous reorganization of the line will be necessary, since the product changes many times each work shift. The aim of the present study is to verify how the BBs methodology is worthwhile in such an area, focusing on a luxury bags packaging line. For these endeavours, we explain the BBs principles for the workers of the assembly line and then we measure the line performance with this new arrangement.

In order to verify the effectiveness of the approach, we compare the results with the actual line performance and the performance of the same line organized with a well-known SALBP optimization algorithm. The results are encouraging, confirming the goodness of such an approach in this context.

The remainder of this paper is organized as follows: section 2 illustrates the theory of BBs and, in section 3, the case study is presented. In the section 4, the experimental results are described while in the last section is a discussion of the results and some concluding remarks.

2. Methods

BBs production is a way of arranging workers on an assembly line in which there are fewer workers than stations. This way of organizing manpower is also called the 'TSS protocol', from the Toyota Sewn Products Management System [27] [28] [29]. The BBs system transforms traditional lines by means of work-sharing.

In order to comprehend how the BBs is organized, the following two TSS rules must be satisfied.

- TSS rule – Forward part: remain devoted to a single item and process it on successive workstations (whereby at any station the worker of a higher index has priority). If your item is taken over by your successor (or if you are the last worker and you have completed processing the item), then relinquish the item and begin to follow the backward part.
- TSS rule – Backward part: walk back and take over the item of your predecessor (or, if you are the first worker, pick up raw materials to start a new item). Begin to follow the forward part. Thus, according to

> this rule, when the last worker finishes the product performing, he walks back upstream to take over the work of his predecessor, who walks back and takes over the work of *his* predecessor, and so on, until, after relinquishing his product, the first worker walks back to the beginning of the line to start a new item.

The workers are obliged to respect their order along the line, but they are not restricted to any subset of stations; instead, they are allowed to move among them, carrying their items as far towards completion as possible; this allows the system to dynamically reallocate work by moving workers. The "reset" moment takes place when the last worker completes a product and each worker leaves his position to restart from the position abandoned by his predecessor and to take over his work; obviously, the first worker always restarts from the beginning of the line.

In conventional production lines, the key design problem is the so-called 'assembly line balancing' (ALB). This means assigning to employees tasks in order to maximize the total value-added worker time. ALB is a central problem when designing or reconfiguring a line [4]. When using the BBs model, and thanks to the TSS procedure, ALB solving is no longer needed because workers are mobile and tasks are continuously assigned to them in real-time.

If we order workers from the start, on the left side, to the end, on the right of the line, we must make a couple of considerations. Normally, a worker on a TSS line may be blocked by his successor to the right, if the latter is slower. Researchers have been investigating whether there is any initial condition that would evolve into an optimal steady-state in which there is no blocking. In such a case, the cycle time of the line would be minimal, the throughput rate maximal, and the workers saturation would be absolute.

The most remarkable results in an analytical study of the BBs were obtained by Bartholdi and Eisenstein [30] [31], who proposed a 'normative model'. In this work, the authors - using a Markov chain - expressed the assumptions needed as a sufficient condition for having a self-balancing in the line.

Later researches have investigated the influence of stochastic operating times; other studies have focused on the BBs dynamics with two workers who, in some sections of the line, are faster but, for rest of the line, are slower [32] [33]. Other special cases have considered modifying the TSS protocol by allowing passing (an employee is allowed to overtake a slower successor) or a BBs implemented with learning curves [34]. One more stimulating feature of BBs is the effect of labour turnover [35] [36]: BBs lines have proved to be more robust, in high labour turnover conditions, than traditional lines. An interesting way of analysing BBs systems is to study the state trajectories of workers [37]. They are the conjunction of the coordinates of n workers (in a n-dimensional space) of every reset. The simulation of BBs has sometimes been used in order to study some particular configuration.

Some approaches similar to BBs which use linear walking-workers have been fully analysed in depth, but have shown more limitations [38]. The main drawbacks are that each worker must be fully trained to complete the whole cycle of a product. It may be expensive or difficult to train every employee for a large number of operations, especially in cases when only relatively low-skilled workers are available [39].

2.1 The Normative Model

The normative model is a smart abstraction of real-world environments. Let us consider a U-shaped line with m workstations; there are fewer workers than stations and they are numbered from 1 to n according to their sequence on the production line, so each worker is associated with a numerical index expressing his position along the line (in each line, $n < m$). The worker with the smallest index is at the beginning of the line. Each instance of the product is called 'item' and all items are identical. Each of them is processed on the same sequence of workstations; the total amount of processing time - the same for all the items - is normalized to one time unit. A station can process at most one item at a time and there is at most one worker at a given station; each worker carries a product from station to station towards completion and independently follows the passing rules.

In a BBs line, the downstream worker always has priority over the upstream worker, who can be blocked during his forward phase if he arrives at a station where the downstream worker is still working. In fact, the TSS rule implies that no passing is allowed, so when blocking occurs between workers i and $i+1$, i must wait until the other, while moving forward, finishes his work or, while moving backward, takes over his work. The only worker who can never be blocked is the final one, of index n.

Bartholdi and Eisenstein [29] have defined a normative model, which is the simplest model to describe a BBs line and which is a useful benchmark to guide the implementations of such a line. This ideal model is based on the following simplifying assumptions:

1. Insignificant walk back time: the total time to assemble a product is significantly greater than the total time for the workers to hand over their work and walk back to get more work.
2. Total ordering of workers by velocity (TOWV): each worker i can be characterized by a work velocity v_i.
3. Smoothness and predictability of work: the work-content of the product is spread continuously and

uniformly along the flow line, the length of which is normalized to 1 and partitioned into intervals corresponding to workstations.

Assumption 1 leads us to conclude that while workers move forward with a finite velocity, their backward velocity can be thought of as infinite such that when the last worker finishes an item and begins moving backward, the others do the same simultaneously; thus, the reset takes place at the same moment for all the workers and is coincident with the moment of handover.

As we can see from Assumption 3, the line is fulfilling the total work content such that it is a segment $[0;1]$and each station is associated with a certain partition of it. If we define p_j as a fixed percentage of the total standard work content of the item, then $p_0 = 0$. Moreover, let $p_k = \sum_{j=1}^{k} p_j$ be the cumulative amount of work performed on the item immediately after it has left the station, $k = 1,2 \dots m$ $\left(\sum_{j=1}^{m} p_j = 1\right)$. Then the interval (p_{k-1}, p_k) represents the quantity of work performed at station k.

The instantaneous position of the worker i on the line is expressed as the cumulative fraction $x_i(t)$ of the work completed on his item at a given moment t; as the TSS rule does not allow workers to pass each other, it follows that $0 \le x_1 \le x_2 \le \cdots \le x_n \le 1$. At any time, the state of the system is represented by the vector of the workers' positions $x = [\,x_1,\ x_2 \dots x_n]$.

From Assumption 2, we have it such that in the normative model, each worker i is ordered by his working velocity $v_i(x)$. In formulae, for every $i < j$ we will have:

$$v_i(x) < v_j(x) \qquad \forall (i \in [1; n-1]; j \in [2; n]) \tag{1}$$

This means that if workers are placed in the line from the slowest (a position 1) to the fastest (a position n), then the line will have neither blocking nor idle time. Every reset is similar to every other, and this steady-state functioning is cost-effective because the cycle time for the line is the smallest (see Figure 1).

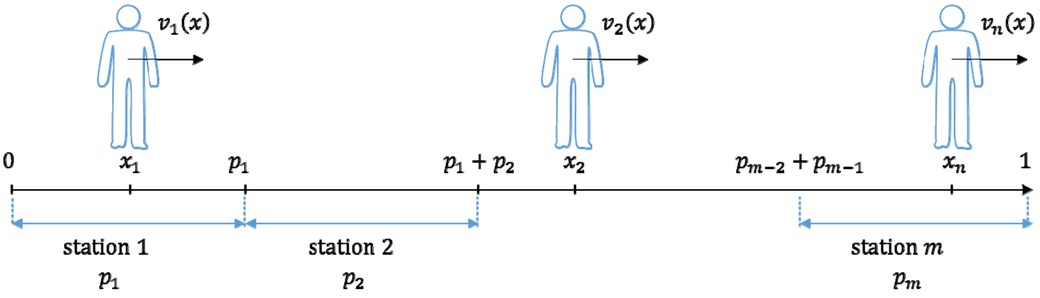

Figure 1. BBs line. The instantaneous position of worker i on the line is expressed as the cumulative fraction $x_i(t)$ of the work completed on his item at a given moment t. $v_i(x)$ is his working velocity. Each station is associated with a certain partition of the total work-content executed.

3. Case Study

The present work focuses on a packaging line for luxury bags. The sequence of operations required for fulfilling the packaging of such leather bags is as follows:

- Insert the product cards that show the company logo and the number and type of quality controls;
- Apply a protective sheet of polyurethane foam on the chrome parts and on those areas that require special protection;
- Insert the bag inside a flannel envelope;
- Insert the envelope in a sheet of tissue paper or in another suitable container (primary packaging);
- Put into a single box or in a container for multiple bags;
- Create the tertiary packaging for transport, through the formation of a pallet;
- Strap and label the boxes.

The packaging line is, therefore, an assembly line in which three or four operators cooperate for the fulfilment of the production volume required.

The most frequent way of organizing an operating unit like this is the line arrangement. The operators are set in sequence in predetermined fixed positions, and each one carries a part of the production cycle.

The division of work between an operator and the other is made by the foreman who, often intuitively, assesses the duration of the required processing times and distributes the tasks among the employees.

The main disadvantage of this configuration - whenever the balance is not perfect - is the creation of a high quantity of WIP, which accumulates between the production stations. The unbalancing of the line is, as a matter of fact, a certain datum. Indeed, the variability of the execution times prevents the station balancing, even if this could be obtainable considering the average processing times.

A second problem is the need to redistribute the job every time that the product changes. Indeed, we know that for a luxury, a wide range of models is an essential requirement. In practice, the products change many times during each work shift.

A further difficulty to be faced during production is the inability of traditional methods to deal with disturbances, such as small faults, short absences or anything else, which results in a loss of performance.

The experimental activity has included the study of four different models, whose processing sequences are displayed in Table 1.

The items listed were chosen to ensure a certain degree of process variability (a variable number of phases among products) and also because, according to the workers, they appear to be the most complex to package. In particular, the step of applying the polyurethane foam is difficult, long and affected by highly variable times.

Phase	Product			
	A	B	C	D
1. Insert card		X	X	X
2. Protective sheet			X	X
3. Flannel	X	X	X	X
4. Tissue paper			X	
5. Boxing	X	X	X	X
6. Pallet	X	X	X	X
7. Strap and label	X	X	X	X

Table 1. Multiproduct process chart. In the table is shown the work actions required by each of the four products tested. The left column shows the assembly phases, while the other columns indicate the product (A, B, C and D).

The simulations were carried out on four different days, spaced by a week. On the first day, the workers were initially assembled in sequence and operated one action each. The assessment of such experimental processing times allowed us to build a reference case that was useful in comparing the following results. After this initial simulation, the operators were disposed according to their traditional routines in order to analyse their actual performance.

On the second experimental day, the line was organized according to the optimization algorithm of Kottas and Lau [40]. This algorithm was resolved by the authors of the present work, based on the evidence gathered during the first simulation day.

On the third day, the BBs methodology was applied. It may be noted that it roughly complied with the normative model assumptions, even if none of them can be considered completely true. The workers, in fact, were arranged from the slowest to the fastest and without allowing overtaking. However, and as a matter of fact, nobody can say whether such a speed would always be steady. The need for a male to perform the final steps (involving fatiguing activities) set up a further constraint for the model.

On the fourth testing day, the BBs line performance was again measured, verifying whether the benefits were modified by a learning factor, as is known in the literature [34].

4. Results

The first product needed four assembling phases. The company-typical production arrangement for this item was a line with three operators, who were also involved in the BBs production model. Table 2 shows the main results of the simulation.

Product A	CT	W	TT	TR	WTR	WIP
	[s/#]	[w]	[s]	[#/min]	[#/h/w]	[#]
Reference line	70	4	751	0,86	12,9	10,7
As-Is	74	3	236	0,81	16,2	3,2
BB	44	3	132	1,36	27,3	3,0

Table 2. Production performance for Product A. In the table is visible the cycle time (CT), the number of workers (W), the throughput time (TT), the throughput rate (TR), the worker specific throughput rate (WTR), and the theoretical work in the process from Little's law. In each line is given the results for the reference line, the actual model and the BBs.

As the results indicate, the production performance of the BBs model is better than the traditional packaging system, considering the increased TR and the great reduction of the TT.

Furthermore, for the second article (see Table 3) we can see significant benefits from the application of the BBs methodology, with a triple specific labour productivity obtained while reducing the work in process and the throughput time. An increased throughput rate of the line can correspondingly be observed.

Product B	CT	W	TT	TR	WTR	WIP
	[s/#]	[w]	[s]	[#/min]	[#/h/w]	[#]
Reference line	71	5	926	0,85	10,1	13,0
As-Is	77	4	478	0,78	11,7	6,2
BB	29	4	116	2,07	31,0	4,0

Table 3. Production performance for Product B. As is clearly visible, the BBs assembly line outperforms the reference case and the traditional line, both in terms of productivity and work in process.

The third product required seven processing stages; hence, the simulation of the "reference line" involved seven operators. The company's production, however, was based on only four employees. Similarly, it was decided to implement the BBs line with four workers. Given that the space available for the workers' movements was not sufficient, it was later decided to also try a BBs with only three operators. An increased fluidity of the line was achieved, while the lower number of workers did not lead to a heavy deterioration of performance. The results can be seen in Table 4

Product C	CT [s/#]	W [w]	TT [s]	TR [#/min]	WTR [#/h/w]	WIP [#]
Reference line	29	7	1075	2,07	17,7	37,1
As-Is	43	4	446	1,40	20,9	10,4
BBs 4	30	4	120	2,00	30,0	4,0
BBs 3	37	3	111	1,62	32,4	3,0

Table 4. Production performance for Product C. In addition, in product C the BBs assembly line shows the best performance. The reduction of the workers from four to three does not significantly affect the specific productivity and improves the lead time (TT) and the throughput rate (TR).

By carefully observing the results presented in the previous table, one can observe how the reduction of the number of operators allows for a reduction of the lead time. This follows from a lower incidence of the backward part of the TSS rule and from a reduced need to manage the handovers. At the same time, however, there is a reduction of the TR of the line due to the reduction of the available manpower.

The fourth product required six steps to be accomplished, as seen in Table 5.

Product D	CT [s/#]	W [w]	TT [s]	TR [#/min]	WTR [#/h/w]	WIP [#]
Reference line	35	6	598	1,71	0,1	17,1
As-is step 1	38	2	7220	1,58	0,1	190,0
As-Is step 2	13	3	7220	4,62	0,2	555,4
BB	31	3	93	1,94	1,9	3,0

Table 5. Production performance for Product D. The most complex product shows how the BBs can suit the packaging line. All the performances are notably enhanced, with an astonishing reduction in the work in process

The problem of the imbalance of the line was particularly marked for this item: some operators had to huddle to complete the first part of the process, while others were particularly idle. To overcome this problem, the company decided to implement the first part of the process operating in a batch on all the products using two operators.

Having once completed this first step, a third operator was added to the line in order to complete the packaging with a team of three people.

The results show that, by means of BBs approach, the productivity of the line can be improved by 55%, while remarkably the throughput time drops by 88%. Such reductions are here more evident because the complexity of the traditional assembly procedure chosen created a high quantity of work in process. Furthermore, the lead time was increased by the need to split the tasks in two different assembling steps. The consequences of this choice also affected the warehouse management, creating an unnecessary accumulation of material near the assembly line and causing bottlenecks in production.

5. Discussion and Conclusion

All the experimental evidence seen seems to agree: the application of the BBs methodology to the luxury bags packaging line has always yielded better performance than those obtained from the organization currently adopted.

The improvements are basically of four types:

1. A reduction in the cycle time: in all the tests it was possible to detect a lowering of the cycle time, with reductions of between approximately 20% and 60%.
2. A reduction in the throughput time of the line. Even in this case, the reduction was observed in all the four products. The reduction was very significant, with a percentage of at least 40% with the higher values near the unit.
3. An increase in the specific productivity per worker. The reduction of the number of operators, combined with the growth of the production rate, led to a significant rise in the number of pieces produced per hour by each operator.
4. A reduction of the WIP. We observe a general reduction of the theoretical WIP, which was obtained by applying Little's law. This analytical value is often lower than that achieved in the real line. This is due to the transient effects of the starting and ending of production, for which the system cannot be considered to be "stable" such that Little's law is only valid approximately [41]. Nevertheless, the reduction of the WIP is highly consistent and increases with the complexity of the product.

Table 6 summarizes the results of the growth in performance that the BBs arrangement provides to the four simulated lines.

	CT [s/#]	W [w]	TT [s]	TR [#/min]	WTR [#/h/w]	WIP [#]
Product A	-41%	0%	-44%	+68%	+68%	-6%
Product B	-62%	0%	-76%	+166%	+166%	-36%
Product C	-30%	25%	-73%	+43%	+8%	-25%
Product D	-18%	0%	-99%	+23%	+910%	-99%

Table 6. Production performance improvement. The table shows the improvement by comparing the BBs arrangement with the traditional organization of the line.

A possible objection to the last comparison made between the line performance could be that such a performance increase might be due, not so much to the goodness of the BBs model, but rather to the bad empirical design of the company. Of course, this consideration might be true; however, it must be emphasized that the situation under analysis is not so uncommon but, conversely, might even be considered to be a typical situation. Very often, in fact, the skills and experience of the line operators are crucial in organizing the production line, as in the real case. Moreover, in this specific case study, the competencies and qualifications of the foremen were quite good and the workload was divided among the operators in a rational manner.

At any rate, it was determined to compare the results of our experiments with those of a line design obtained by applying the well-known SALBP algorithm of Kottas and Lau [40], which was conceived in order to contemplate probabilistic, economic and productive issues, and to produce the best balanced design of the assembly line.

In Table 7, the SALBP results of the line design for product A are shown.

As is clearly visible, although this solution results in an improvement of the cycle time, it also leads to the creation of many semi-finished goods, whose presence strongly expands the throughput time.

Product A	CT [s/#]	W [w]	TT [s]	TR [#/min]	WTR [#/h/w]	WIP [#]
Reference line	70	4	751	0,86	12,9	10,7
As-Is	74	3	236	0,81	16,2	3,2
SALBP	68	3	468	0,88	17,6	6,9
BB	44	3	132	1,36	27,3	3,0

Table 7. Product A's packaging performance with SALBP. The table gives, in the third row, the performance of the line when designed according to the optimization algorithm. The cycle time is reduced compared to the traditional way, but the throughput time and the WIP increase.

The results of the application of the SALBP algorithm to all four products manufactured are visible in Table 8.

As can be seen in the reported data, the SALBP algorithm allows for a dimensioning of a line, which performs only better than the line usually conceived in the company. Conversely, in some aspects, such as the amount of WIP and the TT, the algorithm produces worse results. This is justified by the fact that the algorithm takes into account the uncertainty of working times and the costs of working and reworking, but does not optimize the amount of the WIP. Consequently, the WIP and the TT are higher than in the traditional case.

	CT [s/#]	W [w]	TT [s]	TR [#/min]	WTR [#/h/w]	WIP [#]
Product A	68	3	468	0,88	17,6	6,9
Product B	69	4	884	0,86	13,0	12,7
Product C	39	4	816	2,14	22,4	20,2
Product D	36	3	421	1,81	0,6	15,2

Table 8. Assembly line performance when designed with the SALBP algorithm. The system always improves the cycle time, but the amount of the WIP increases as well as the TT.

To summarize, we can say that the application of BBs to the packaging of luxury handbags exhibited several advantages compared to both analytical SALBP dimensioning and the usual design made in the company by the production manager, based on empirical and practical criteria. These benefits are summarized in the following points:

- Self-design of the line: once the operators have learned the rules of the BB, they are able to assemble any bag without the need for redesigning the assembly activities.
- Increased production performance: in all the simulations, we have seen a significant increase in performance. The cycle time always improves, as does the TT. Nonetheless, the best outperforming parameters are the throughput time and the worker hourly throughput rate.
- In some cases, a visible benefit is the reduction of the workforce needed to achieve the same production capacity.
- Although the normative model's hypotheses do not apply perfectly, nevertheless the performance of the BBs line are absolutely satisfactory, even though they are not the best that is theoretically achievable.
- The compliance of the BBs model with production anomalies was very high. We were able to observe how the production line was able to manage itself without problems, short absences of an operator, the small breaks necessary to supply semi-finished materials or small work interruptions on the part of some operators, and so on, without compromising the line availability [42].

Finally, we were able to roughly test the effect of operators' learning: after a few days of the application of the methodology, i.e., on the fourth day of the test- we could observe how the production performance further improved by reducing the time needed to set up the line and begin production after a product change. The improvement in performance was an increase of the average TR of around 10% for product C. Anyway, not much more can be stated since the experimental results were too small to be statistically significant.

Further research could evaluate the benefits of the BBs methodology in this particular area, thanks to the application of advanced engineering tools - such as discrete event simulation – in an attempt to stress the system under conditions that are not experimentally achievable in a real company. We must remember, in fact, that the experiments were conducted during real production stages and, therefore, it was not possible to stress the system without running the risk of compromising the line's productivity.

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