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SOLUTION OF THE BUFFER ALLOCATION PROBLEM USING THE OVERALL EQUIPMENT EFFECTIVENESS INDICATOR IN A SERIAL PRODUCTION LINE

José Omar Hernández-Vázquez[1], José Israel Hernández-Vázquez [1, *], Salvador Hernández-González[2], and Daniel Arturo Olivares-Vera[3]

[1]Department of Industrial Engineering
Tecnológico Nacional de México/Instituto Tecnológico de León
León Guanajuato, México
[*]Corresponding author's e-mail: joseisrael.hernandez@leon.tecnm.mx

[2]Department of Industrial Engineering
Tecnológico Nacional de México/Instituto Tecnológico de Celaya
Celaya Guanajuato, México

[3]Department of Economic and Administrative Sciences
Tecnológico Nacional de México/Instituto Tecnológico de León
León Guanajuato, México

This paper presents an analysis of the buffer allocation problem on a serial production line with five workstations and four buffer locations with unreliable operating conditions. Originally, this work was used as an optimization criterion to maximize the Overall Equipment Effectiveness indicator; said indicator is used to evaluate the performance of the processes in Lean Manufacturing; a comparison of the generated solution configurations is made with respect to other optimization criteria such as the minimization of the average work-in-process inventory and the maximization of Throughput. Three case studies involving the production line operating in a balanced and unbalanced manner are examined. The evaluation method used in this document is simulation. On the other hand, an exhaustive enumeration of the analyzed solution space is made. The results report the optimal allocation of buffers in the case studies and the differences that exist in the distribution of these in the optimization criteria investigated.

Keywords: Buffer Allocation Problem; Overall Equipment Effectiveness; Work-in-process Inventory; Throughput; Simulation; Lean Manufacturing.

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1. INTRODUCTION

The buffer allocation problem (BAP) is classified as an NP-Hard combinatorial optimization problem in production lines design (Demir *et al*., 2014; Weiss *et al*., 2019). This consists of defining the allocation of storage places (buffers) within a production line to maximize the efficiency of the process (Hernández-Vázquez *et al*., 2022a; Koyuncuoğlu and Demir, 2023). This problem still has great scientific relevance due to its complexity and the great diversity of solution configurations reported in the literature, according to the optimization criteria used (Demir *et al*., 2014; Weiss *et al*., 2019; Magnanini *et al*., 2022).

A production line is organized with workstations connected in series and separated by buffers (Koyuncuoğlu and Demir, 2023). The main reason for maintaining buffers is to allow workstations to operate independently of each other (Hernández-Vázquez *et al*., 2019). Buffers have a significant impact on improving the efficiency of the production line by eliminating detrimental effects due to failures or variations in processing times (Kose and Kilincci, 2020; Hernández-Vázquez *et al*., 2022a; Ho *et al*., 2022). However, companies face the problem of controlling the amount of accumulated work in the process, so the definition of the number of buffers between each station should be limited and should not be a trivial decision for managers, administrators, and supervisors (Hernández-Vázquez *et al*., 2022b).

In the existing literature, a wide variety of optimization criteria are reported in the study of BAP with formulations of one or more objectives (multi-objective). In Table 1, the works with the greatest impact in this area in recent years are mentioned. These are classified according to the optimization criteria used. Maximizing the average production rate or throughput (TH), minimizing the total buffer size, minimizing the average work-in-process inventory (WIP), minimizing total cost, and minimizing cycle time (CT) are the most popular criteria in the BAP study.

The vast majority of the solution strategies reported in the BAP study consider implementing an evaluation method and an optimization method jointly (Demir *et al*., 2014; Weiss *et al*., 2019). With regard to evaluation methods, analytical methods and the simulation stand out, meta-models have recently been developed based on results obtained with the simulation (Amiri and Mohtashami, 2012; Mohtashami, 2014; Hernández-Vázquez *et al*., 2022a,b); the application of these helps in the analysis of complex production systems, taking advantage of one of the main assets of simulation, and allows optimization methods to significantly improve their computational efficiency. Respecting the latter, there is a wide variety of procedures used. However, metaheuristic techniques and hybrid algorithms that have generated high-quality solutions to this problem stand out (Hernández-Vázquez *et al*., 2019; Kose and Kilincci, 2020; Gao, 2022; Hernández-Vázquez *et al*., 2022a; Xi *et al*., 2022; Kassoul *et al*.,2023).

This paper presents an analysis of the BAP, it seeks to maximize the Overall Equipment Effectiveness (OEE) indicator in an original manner as an optimization criterion, which turns out to be of great importance in the Lean Manufacturing approach and that its use has not been previously reported in research on the BAP. A serial production line with five workstations and four buffer locations with unreliable operating conditions is examined under three case studies. The use of this indicator and measuring the impact of buffers on it are the most relevant contributions of this document.

Another aspect to highlight is the comparison that is made of the optimal buffer configurations generated with the criterion mentioned in the previous paragraph, with respect to those obtained with two of the most popular criteria in the study in the BAP, such as minimize WIP and maximize TH. The evaluation of the production line is done through the simulation software PROMODEL; which was designed to study manufacturing processes of one or more products, assembly, and transformation lines, among others (García-Dunna *et al*., 2013). Such software was previously used successfully by Hernández-Vázquez *et al*. (2022a) in the BAP solution.

The rest of this document is organized as follows. The concept of OEE is explained in the subsequent section. Sections 3 and 4 mention the formulation of the BAP and the case studies analyzed. The description of simulation model and experiments is presented in section 5. The numerical results are shown in section 6, and finally, a section of conclusions is presented, in which the scope of the results generated and future lines of research are addressed.

2. LEAN MANUFACTURING AND OEE

Lean Manufacturing is the name given to the just-in-time (JIT) system in the West. It is also called a world-class manufacturing and Toyota production system. It can be defined as a continuous and systematic process of identification and elimination of waste or excesses, understanding as excess all that activity that does not add value in a process but cost and work (Socconini, 2019; Hernández-Vázquez *et al*., 2021). Toyota classifies waste into seven large groups:

- Muda of overproduction.
- Muda of over-inventory (WIP in excess).
- Muda of defective products.
- Muda of materials transportation and tools.
- Muda of unnecessary process.
- Waiting Muda.
- Muda of unnecessary worker movements.

One of the most important measurements in Lean Manufacturing is the OEE indicator. This represents the time that is actually worked, without downtime, at the established capacity and without defects. It is also the fraction of time usable from the available time (Socconini, 2019). Equation (1) expresses, in general, the way to obtain this value (Stamatis, 2017; Socconini, 2019; Singh *et al*., 2021):

$$\mathrm{OEE} = \mathrm{Availability} \times \mathrm{Performance} \times \mathrm{Quality} \tag{1}$$

Table 1. BAP Literature review

Authors	**Optimization criterion**					
	Max TH	**Min Total buffer size**	**Min WIP**	**Min Cost**	**Min CT**	**Others**
Yuzukirmizi and Smith (2008)	*	*				Min total average waiting delay
Chehade *et al*. (2010)	*	*				
Abdul-Kader *et al*. (2011)	*				*	Max maintenance time
Amiri and Mohtashami (2012)	*	*				
Cruz *et al*. (2012)	*	*				
Bekker (2013)	*	*				
Li (2013)		*				
Mohtashami (2014)	*			*		
Nahas *et al*. (2014)	*					
Narasimhamu *et al*. (2014)	*					
Wang *et al*. (2014)	*					
Kose and Kilincci (2015)	*					
Köse *et al*. (2015)	*					
Weiss and Stolletz (2015)		*				
Oesterle *et al*. (2016)	*			*		Min idle time
Wang *et al*. (2016)	*			*		
Dolgui *et al*. (2017)	*			*		
Nahas (2017)				*		
Patchong and Kerbache (2017)	*					
Zandieh *et al*. (2017)	*	*				Min total number of defective units
Lin and Chiu (2018)	*					
Nahas and Nourelfath (2018)		*				
Ouzineb *et al*. (2018)				*		
Zhou *et al*. (2018)						Max system availability
Bamporiki *et al*. (2019)	*		*			
Hernández-Vázquez *et al*. (2019)			*			
Motlagh *et al*. (2019)	*	*		*		
Renna (2019)	*			*		
Alfieri *et al*. (2020)				*		Max average completion time
Gao *et al*. (2020)	*					
Kose and Kilincci (2020)	*	*				
Alaouchiche *et al*. (2021)	*					Min energy consumption
Koyuncuoğlu and Demir (2021)	*					
Shaaban and Romero-Silva (2021)	*	*				
Gao (2022)	*					
Hernández-Vázquez *et al*. (2022a)	*			*		
Hernández-Vázquez *et al*. (2022b)					*	
Magnanini *et al*. (2022)	*					

Authors	**Optimization criterion**					
	Max TH	**Min Total buffer size**	**Min WIP**	**Min Cost**	**Min CT**	**Others**
Shao *et al*. (2022)	*			*		
Xi *et al*. (2022)				*		
Gao and Liu (2023)	*					Min energy consumption
Kassoul *et al*. (2023)	*					
Koyuncuoğlu and Demir (2023)						Max profit

To determine each of the components of this indicator, it is necessary to obtain the process information daily, analyze it and make the following calculations (Equations 2-5). The most relevant data for the OEE calculation that must be identified are the available time of the working day, the downtime generated in the workstations, the total production achieved, the production capacity in the manufacturing line, and the number of defects and rework generated. It is important to clarify that the Availability, Performance and Quality components are measured as a percentage (0 to 100). Therefore, the ideal value of the OEE indicator is 100%.

$$\text{Operating time} = \text{Available time} - \text{Downtime} \tag{2}$$
$$\text{Availability} = (\text{Available time} - \text{Downtime}) \div \text{Available time} \tag{3}$$
$$\text{Performance} = \text{Total production} \div (\text{Operating time} \times \text{Capacity}) \tag{4}$$
$$\text{Quality} = (\text{Total production} - \text{Defects and rework}) \div \text{Total production} \tag{5}$$

3. FORMULATION OF THE BAP

In this study, BAP is analyzed through three mathematical models. The first aims to maximize the OEE indicator, the second to minimize WIP, and the third to maximize TH; being the first model the one that presents an innovation in the study of this by the criterion of optimization investigated. Next, each of the mentioned models is set out below.

3.1 Formulation 1

$$\begin{aligned}&\text{Find } B = (B_1, B_2, \dots, B_n) \text{ to}\\&Max\ Z = OEE(B)\end{aligned} \tag{6}$$

Subject to

$$\sum_{i=1}^{n} B_i = N \tag{7}$$
$$B_i \geq 1 \tag{8}$$
$$B_i \geq 0 \text{ and integers} \tag{9}$$

where:

- B_i = Variable of decision or number of buffers in the buffer location *i*
- n = Number of buffer locations
- N = Total buffers available
- $OEE(B)$ = Value of the OEE indicator, considering B

3.2 Formulation 2

$$\begin{aligned}&\text{Find } B = (B_1, B_2, \dots, B_n) \text{ to}\\&Min\ Z = WIP(B)\end{aligned} \tag{10}$$

Subject to

$$\sum_{i=1}^{n} B_i = N \tag{11}$$

$$B_i \geq 1 \tag{12}$$

$$B_i \geq 0 \text{ and integers} \tag{13}$$

where:

- $WIP(B) =$ Value of WIP, considering B

3.2 Formulation 3

$$\text{Find } B = (B_1, B_2, \dots, B_n) \text{ to} \quad Max\ Z = TH(B) \tag{14}$$

Subject to

$$\sum_{i=1}^{n} B_i = N \tag{15}$$

$$B_i \geq 1 \tag{16}$$

$$B_i \geq 0 \text{ and integers} \tag{17}$$

where:

- $TH(B) =$ Value of TH, considering B

Mathematical models contemplate constraints that are related to the total number of buffers and the allocation of at least one buffer in each buffer location.

4. CASE STUDIES

This section defines the three case studies to be analyzed, these are based on a series production line with five workstations and four buffer locations, similar to the one analyzed by Papadopoulos *et al*. (2009). Figure 1 shows its structure, and the circles indicate the workstations and the rectangles represent the buffer locations of the work-in-process inventory. The material flows from the outside of the system to W_1, then to B_1, lately to W_2, and so on until it reaches W_5; finally, the final product leaves the process. It is considered that the first station will not suffer from a shortage of material and that the last one will never be blocked.

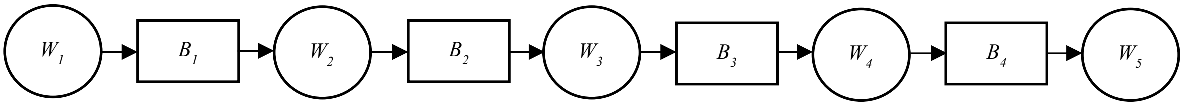

Figure 1. Serial production line

The operating conditions are not reliable in the production line. Table 2 illustrates the mean time to failure (MTTF) and mean time to repair (MTTR) existing in it. Such times are handled with a Normal distribution (N).

Table 2. MTTF and MTTR in minutes

	Workstations				
	1	2	3	4	5
MTTF	N(200-10)	N(180-13)	N(300-12)	N(190-8)	N(250-5)
MTTR	N(30-5)	N(20-2)	N(18-4)	N(25-3)	N(10-2)

The case studies contemplate the production line operating in a balanced and unbalanced way (with bottlenecks). These are presented below:

- Case 1: Balanced production line.
- Case 2: Production line with a bottleneck (workstation 3).
- Case 3: Production line with two bottlenecks (workstations 2 and 4).

Table 3 indicates the processing times in the workstations; these maintain an Exponential distribution behavior (E) in the different case studies.

Table 3. Process time in minutes

	Workstations				
	1	2	3	4	5
Case 1	E(1)	E(1)	E(1)	E(1)	E(1)
Case 2	E(1)	E(1)	E(2)	E(1)	E(1)
Case 3	E(1)	E(2)	E(1)	E(2)	E(1)

5. SIMULATION MODEL AND EXPERIMENTS

A simulation model of the production line was made through the PROMODEL software, the study considered 10 replicas for each combination of buffers. The simulation time was 8 hours for each replica, with a warm-up time of 2 hours. The PC where these simulations were performed includes an AMD Ryzen 3 4300U processor with Radeon Graphics 2.70 GHz and 8GB of RAM.

The analysis considered an exhaustive enumeration of the entire space of solutions from the mathematical models presented. The allocation of N buffers was conducted in each of the case studies investigated in a range of 4 to 10. Table 4 presents the number of solution combinations generated for each N value examined, that is, the space of solutions. 210 buffer configurations were evaluated in each optimization criterion, which is to say a total of 630 configurations for the three criteria investigated.

Table 4. Solution space

N	**Buffer configurations**
4	1
5	4
6	10
7	20
8	35
9	56
10	84

6. NUMERICAL RESULTS

In this section, the optimal solutions obtained in the three case studies are reported. Tables 5-7 present the results generated for the different values of N. It is important to note that the units of measurement in the optimization criteria are:

- OEE → %.
- WIP → Parts.
- TH → Pieces per minute.

In a preliminary analysis of these tables, the OEE and TH optimization criteria report the maximum values of these when 10 buffers (N=10) are assigned in the three case studies presented. On the other hand, the minimum WIP values were obtained when 6 buffers were allocated (N=6).

Table 5. Optimal buffer configurations of case 1

N	**Optimization criteria**	***B*₁**	***B*₂**	***B*₃**	***B*₄**	**Optimal value**
4	OEE	1	1	1	1	38.64
	WIP	1	1	1	1	5.9
	TH	1	1	1	1	0.4804
5	OEE	1	1	1	2	39.17
	WIP	1	1	1	2	5.9
	TH	1	1	1	2	0.4967
6	OEE	1	2	1	2	39.28
	WIP	1	1	1	3	5.86
	TH	1	1	3	1	0.5054
7	OEE	1	2	2	2	41.34
	WIP	1	1	1	4	5.95
	TH	1	2	2	2	0.5319
8	OEE	2	2	1	3	41.89
	WIP	1	1	1	5	6.02
	TH	1	2	3	2	0.5423
9	OEE	1	5	1	2	42.60
	WIP	1	1	1	6	5.92
	TH	2	3	3	1	0.5544
10	OEE	3	2	2	3	43.83
	WIP	1	1	1	7	6.08
	TH	2	3	3	2	0.5654

Table 6. Optimal buffer configurations of case 2

N	**Optimization criteria**	***B*₁**	***B*₂**	***B*₃**	***B*₄**	**Optimal value**
4	OEE	1	1	1	1	58.54
	WIP	1	1	1	1	5.54
	TH	1	1	1	1	0.3638
5	OEE	1	2	1	1	60.53
	WIP	1	1	1	2	5.43
	TH	1	2	1	1	0.3756
6	OEE	1	2	2	1	61.12
	WIP	1	1	1	3	5.41
	TH	1	2	2	1	0.3854
7	OEE	2	2	2	1	62.64
	WIP	1	1	3	2	5.58
	TH	2	2	2	1	0.3929
8	OEE	2	3	2	1	63.78
	WIP	1	1	1	5	5.52
	TH	2	3	2	1	0.4060
9	OEE	3	2	3	1	63.19
	WIP	1	1	1	6	5.52
	TH	3	3	2	1	0.4004
10	OEE	3	2	4	1	64.48
	WIP	1	1	1	7	5.52
	TH	1	3	5	1	0.4117

Table 7. Optimal buffer configurations of case 3

N	**Optimization criteria**	B_1	B_2	B_3	B_4	**Optimal value**
4	OEE	1	1	1	1	50.08
	WIP	1	1	1	1	5.73
	TH	1	1	1	1	0.3138
5	OEE	1	1	2	1	50.87
	WIP	1	1	1	2	5.61
	TH	1	1	2	1	0.3263
6	OEE	3	1	1	1	53.05
	WIP	1	1	1	3	5.48
	TH	1	3	1	1	0.3363
7	OEE	1	2	3	1	52.23
	WIP	1	1	1	4	5.55
	TH	1	2	2	2	0.3356
8	OEE	1	3	2	2	52.82
	WIP	1	1	1	5	5.55
	TH	1	4	2	1	0.3460
9	OEE	1	3	2	3	53.97
	WIP	1	1	1	6	5.55
	TH	1	4	3	1	0.3556
10	OEE	2	4	3	1	54.96
	WIP	1	1	1	7	5.55
	TH	1	7	1	1	0.3615

Another aspect to examine in the case studies is the behavior of the figures obtained in the optimization criteria and their evolution when increasing *N*. Figure 2 shows the conduct of the OEE. From this graph, it can be deduced that case 2 reports the highest percentages of it despite the fact that it is an unbalanced production line. Even case 3 presents better values than when the line operates in a balanced manner (case 1). For its part, Figure 3 illustrates the behavior of the WIP, from which it can be inferred that case 2 presents the minimum values, except for *N*=7. Finally, Figure 4 indicates the evolution of TH. It can be seen that case 1 presents the best production levels, which concurs with what is presented in (Kose and Kilincci, 2015). As there are a greater number of bottlenecks in the production line, production levels tend to decrease.

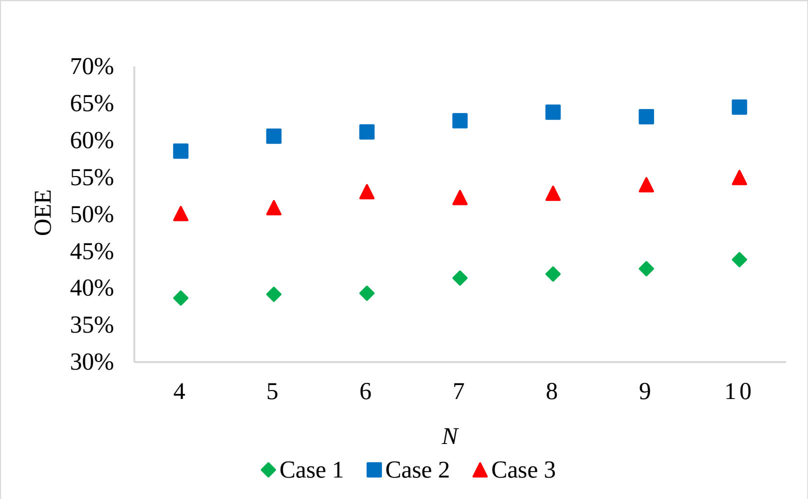

Figure 2. OEE vs. *N*

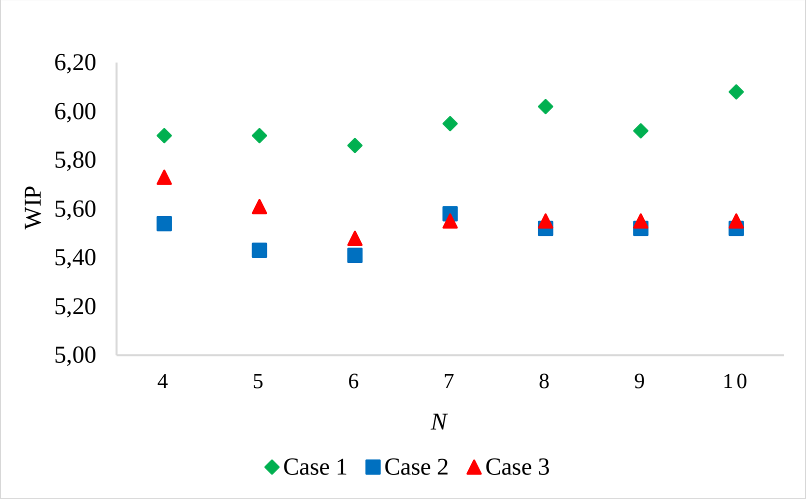

Figure 3. WIP vs. *N*

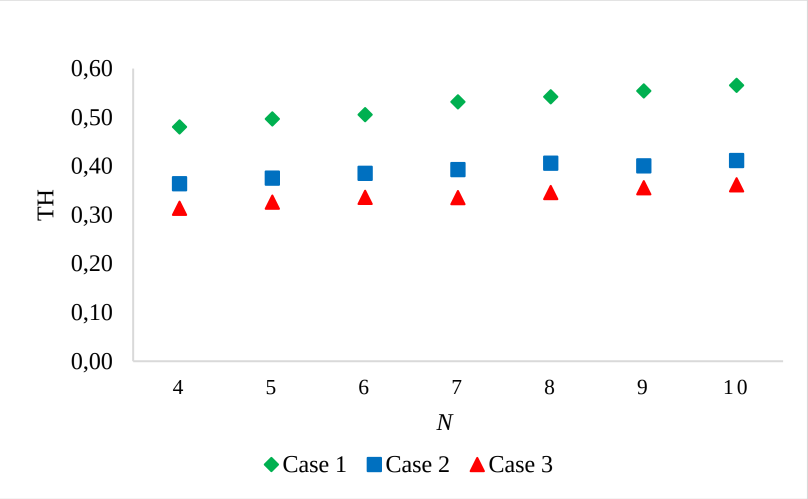

Figure 4. TH vs. *N*

Regarding the percentage of the distribution of buffers allocated in the buffer locations (see Figures 5-7), these present different patterns according to the optimization criterion evaluated. In Figure 5, it can be seen that in the buffer configurations that maximize the OEE, the buffer locations B_2 and B_3 were the ones that presented the highest allocation of buffers when the production line operated in an unbalanced manner (cases 2 and 3); however, for case 1 this occurs in areas B_2 and B_4.

With respect to WIP, Figure 6 shows that the buffer location with the greatest impact on buffer allocation was B_4. This behavior is consistent with what was previously stated by Hernández-Vázquez *et al*. (2019). They indicate a clear tendency to allocate a greater number of buffers towards the end of the production line to minimize WIP in series production lines.

Regarding the TH, Figure 7 shows that the buffer locations with the highest allocation of buffers were B_2 and B_3 in the three case studies, that is, in the central part of the production line. This type of distribution resembles those previously exposed by (Kose and Kilincci, 2015).

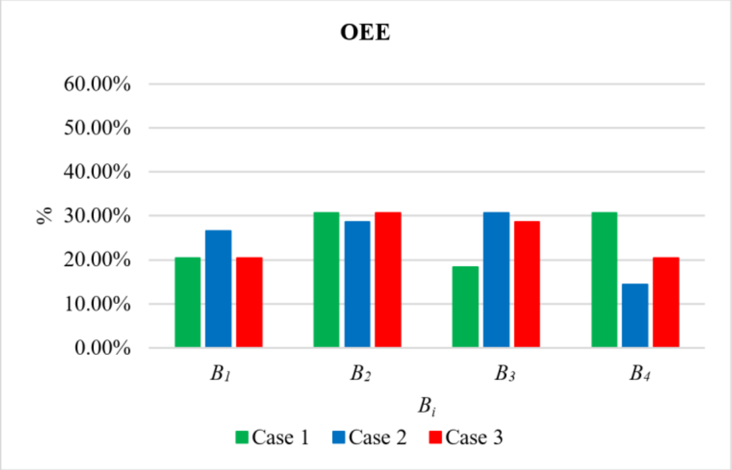

Figure 5. Buffer distribution percentages for OEE

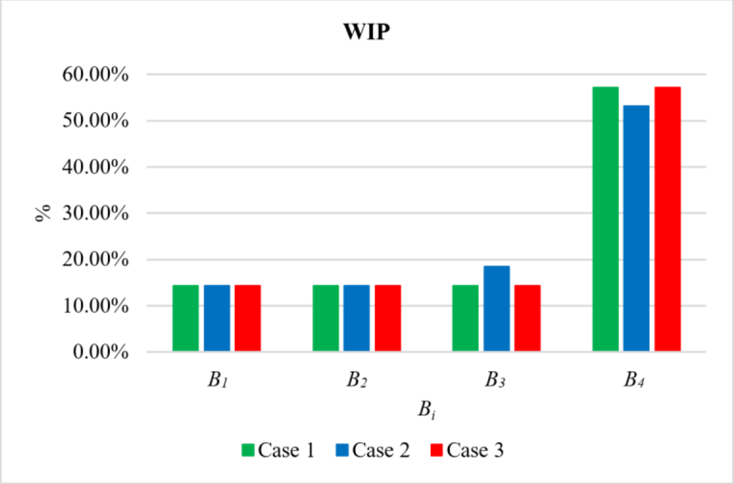

Figure 6. Buffer distribution percentages for WIP

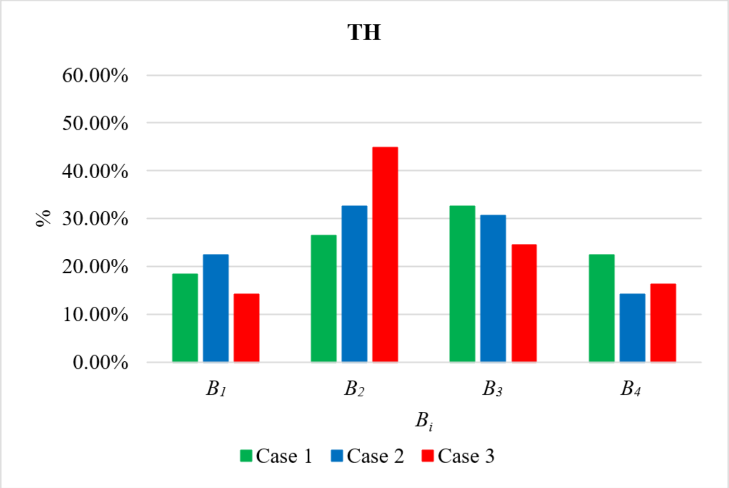

Figure 7. Buffer distribution percentages for TH

7. CONCLUSIONS

The main contribution of the present research is the resolution of the BAP using the maximization of the OEE indicator as an optimization criterion in a series production line with five workstations and four buffer locations with unreliable characteristics. A comparison of the optimal solutions generated with this criterion was made with respect to other popular ones in the BAP study, such as minimizing WIP and maximizing TH. Three case studies were considered in which the production line operated in a balanced or even unbalanced manner; the simulation of this was done through the PROMODEL software.

The results obtained indicate that, unlike the TH, the maximum values of the OEE are not subject to balanced production lines. When the production line operated with a bottleneck (case 2), the OEE indicator reached its best levels. Another important finding was that, although the philosophy of Lean Manufacturing encourages reducing WIP since it is considered a waste (Socconini, 2019), the optimal solution configurations that maximized the OEE indicator presented a very different behavior to those that managed to minimize the WIP; nonetheless, these configurations are a little more like those generated to maximize the TH. One conjecture of all this is that optimal OEE buffer configurations will not always meet the reduction of all waste raised in the Lean Manufacturing philosophy.

The increase in the number of buffers allocated (N) allowed us to generate better solutions for the OEE optimization criterion. In further research, a point of analysis would be to detect the optimal value of N (if possible) that maximizes the OEE indicator, either in the same production line or to study longer production lines through heuristic and metaheuristic procedures as optimization methods. Another area of research would be to test the optimal buffer configurations presented in this document on real production lines and evaluate the impact of these in a practical way under the Lean Manufacturing approach. Finally, other recommendations would be to evaluate the behavior of OEE in production lines that present a structure different from a series. Even solving the BAP under a multi-objective approach, being the OEE one of those objectives.

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