ISSN 2683-345X

journal homepage: http://ijiemjournal.uns.ac.rs/

International Journal of Industrial Engineering and Management

Volume 15 / No 3 / September 2024 / 182 - 195

Original research article

Assessing the impact of a dynamic allocation of continuous improvement in flow shop under uncertain conditions

P. Renna[a,*] 0000-0003-0313-6328

[a] *Università degli Studi della Basilicata, School of Engineering, Potenza, Italy*

ABSTRACT

The competitiveness of the companies depends on continuous progress, and the allocation of the continuous improvement is crucial in today's market competition. The main approaches proposed in the literature are distributed and centralized policies. This research proposes a novel model for resource allocation that surpasses existing methods. It leverages throughput rate evaluation as the core principle. This model considers key improvement parameters and utilizes a mathematical framework to allocate improvement resources to each parameter. The experiments conducted concern failure parameters (Mean Time Between Failures and Mean Time To Repair), setup time, defective rate, bottleneck numbers and the increasing processing time of the bottleneck. The original contribution is twofold: the evaluation considers a wider range of conditions and their impact on flow line's sustainability. The model emphasizes sustainability by focusing on minimizing the idle time of workstations within the flow line. Numerical analysis of the proposed model reveals a substantial reduction in total idle time improving the related energy consumption. Furthermore, the model achieves a throughput rate that closely aligns with the centralized policy, traditionally considered the most effective approach.

ARTICLE INFO

Article history:

Received December 6, 2023
Revised May 28, 2024
Accepted June 21, 2024
Published online July 12, 2024

Keywords:
Continuous improvement;
Variability;
Bottleneck;
Sustainability;
Simulation

*Corresponding author:
Paolo Renna
paolo.renna@unibas.it

1. Introduction

Companies must continually maintain and enhance their global competitiveness This critical aspect compels entire organizations to plan and implement continuous improvement programs [1], [2]. At the shop floor level, the allocation of improvement programs enables the enhancement of manufacturing system performance under both standard conditions and uncertain events. Significant areas where improvement programs can have an impact include bottleneck mitigation, setup, failures, and quality control. The allocation policy plays a decisive role in improving manufacturing system performance by focusing on specific areas for improvement. Previous works in the literature have focused on two allocation models: distributed and centralized. The centralized allocation model directs improvements to the Capacity Constraint Resource (CCR) [3]. The distributed allocation model uniformly distributes improvements across all resources [4]. A combination of the centralized and distributed models is tested as a hybrid strategy [5]. The areas of improvement considered in

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

https://doi.org/10.24867/IJIEM-2024-3-356

the literature are process time variability, setup time, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), defective rate; this research extends the evaluation to the number of bottlenecks and the effect of the higher processing time of the bottlenecks in the manufacturing system. The study of additional parameters allows to better understand the behavior of the allocation models.

The setup comprises both internal and external components, where internal setup involves stopping the machine, and external setup pertains to machine operation [6]. The improvement focuses on reducing internal setup time for preparing the machine for a new task or converting internal setup to external setup [7]. The defective rate caused by machines increases machine utilization due to the need to replace defective products [7]. The Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) impact machine availability and depend on the maintenance policy of the production system.

The design of the flow line, along with task allocation, can result in a bottleneck that limits the system's throughput rate. Therefore, this study considers both the number of bottlenecks and the increase in processing time at the bottleneck.

Another limit of the works proposed in the literature is that the strategies proposed in the literature are static and do not handle the uncertainty of all the stations that compose the flow line.

The proposed model is dynamic able to handle the fluctuations of the manufacturing system and compared to the past works the research questions are the following. The first research question of this paper is as follows:

RQ1: *Can the proposed allocation model improve the performance of the flow line compared to the benchmark models proposed in the literature?*

Considering the critical issue of energy consumption, a reduction strategy, such as the introduction of a switch-off policy, is proposed to decrease energy consumed in the idle state. Therefore, the second research question is as follows:

RQ2: *Can the proposed allocation model reduce the idle state of workstations without impacting manufacturing performance measures?*

The research presented in this paper focuses on using a throughput time formulation of each station of the line to assess how different areas (failures, setup, bottleneck, and quality) can impact this value.

The estimation of this value for each station provides information to evaluate the cycle time of the line. Subsequently, a mathematical model is proposed to allocate a limited budget for improvements in these areas. The objective function of the mathematical model developed is to minimize the cycle time estimation of the line. This model addresses two key issues related to the allocation of improvement programs: how to distribute improvements among the machines and which parameters to enhance.

The available budget level for improvements is taken into consideration to analyze the numerical results. The improvement in potential throughput rate is compared to the two main benchmarks (centralized and distributed) proposed in the literature. Another original contribution involves computing the total idle time as an evaluation of energy consumption in machines in the idle state, which is significant from a sustainability standpoint. The power demand of an operation can be divided into a variable and fixed part. The fixed part ensures the operational readiness of the machines, and it can account for over 30% of the energy consumed when the machines are operational [8], [9]. Reducing this fixed energy component can enhance the sustainability of manufacturing systems.

The paper is organized as follows: Section 2 provides an overview of the literature; Section 3 describes the benchmarks and the proposed improvement policy. Section 4 presents the experiments and numerical results, while Section 5 offers conclusions and outlines future research paths.

2. Literature review

This section presents recent studies on methods for allocating improvement programs, with a major focus on the flow shop context. Godinho Filho and Uzsoy [10] and Godinho Filho [11] investigated the introduction of continuous improvement programs in flow shop systems, considering lot size for setup, MTBF, MTTR, process time variability, and defect rate, and their effects on cycle time. Godinho Filho and Uzsoy [12] examined improvement allocation on MTTR and setup times for a single production station. Numerical results indicated that concentrating efforts on a single area is more effective than spreading improvements across multiple areas. Godinho Filho and Utiyama [13] and Godinho Filho and Uzsoy [14] explored centralized and distributed allocation policies in a flow shop system using simulation models based on system dynamics. Areas of improvement studied included arrival variability, process variability, defect rate, time to failure, repair time, and setup time. Simulation results highlighted that centralized and distributed approaches yield similar results when utilization is low, whereas centralized is a better choice when utilization is higher.

Renna [15] investigated improvement allocation programs in job-shop manufacturing systems. The proposed model is based on workload evaluation, and three allocation policies were developed: centralized, distributed, and proportional. Simulation results demonstrated that the centralized approach performs better in static conditions, while the proportional approach works better in dynamic conditions. Renna [16] examined the allocation of improvements in flow shop systems that manufacture multiple products with bottleneck shifting. They studied centralized, distributed, and proposed a hybrid allocation model. Simulation results indicated that the proposed model is more adaptable to bottleneck shifting than the centralized approach. Renna and Ambrico [17] expanded on previous works by incorporating additional performance measures such as throughput, lead time, work in process, average utilization, and defective products for each workstation in the production line. Simulation results demonstrated that the centralized policy is superior in single-product scenarios, while the hybrid policy yields better results in the case of multi-products.

Utiyama et al. [18] investigated strategies for allocating improvement programs in a flow shop with two capacity-constrained resources. They emphasized that focusing on the bottleneck is a better strategy when the available budget is higher, whereas the hybrid strategy performs better with a lower budget. Wu et al. [19] introduced a Generalized Process of Ongoing Improvement approach in flow shop systems. They illustrated how improving a front-end machine in a production line can be more effective than enhancing the bottleneck. The interconnections among stations are crucial for the allocation of improvement policies. Utiyama et al. [20] explored improvements considering manufacturing setup time and time between failures. The simulations conducted suggested that the goal is to mitigate extreme events. This strategy allows for a reduction in the lead time of manufacturing systems with lower investments. Govoni et al. [21] evaluated six improvement methods through simulation models, three of which are based on the theory of constraints. Numerical results highlighted the relevance of balance degree for choosing the appropriate improvement method. Balanced systems require improvements across all resources, while unbalanced systems need to focus on resources with a high degree of utilization. Kumbhar et al. [22] proposed a digital twin framework to detect, diagnose, and improve bottleneck resources using utilization-based bottleneck analysis, process mining, and diagnostic analytics. The improvement of the bottleneck concerns the evaluation of mean processing time, MTBF, MTTR, setup time. The proposed model is tested in a real manufacturing system with throughput improvement of 10%. Grznár et al. [23] used advanced simulation techniques, seamless data integration, and process optimization to support the development of robust and efficient adaptive manufacturing systems. The focus is to obtain a dynamic layout of a flow line to improve the robustness of the system. Magnanini and Tolio [24] developed a novel Digital Twin model based on analytical model for performance evaluation of manufacturing system embedding evaluation of joint parameter variations is introduced. The model concerns mean processing time, MTBF, MTTR that works dynamycally. The method is proved in a real industrial case in the railway sector. Javaid et al. [25] argued that the integration of Flexible Manufacturing Systems (FMS) with Internet of Things (IoT), big data, Artificial Intelligence, cloud computing, and simulation is considered a key element to improve the resilience and flexibility of manufacturing systems. Digital twins and simulation can expedite the implementation of improvement allocation programs, responding rapidly to market changes.

Table 1 categorizes the main issues discussed in the above overview of recent literature. The classification is based on the manufacturing systems studied: single machine, flow line, and job-shop; the parameters subject to improvement allocation; the use of simulation (Sim.) as a method to study performance; the introduction of dynamic allocation models in terms of parameters and resources; the evaluation of different budget levels for improvement allocation; and the assessment of performance measures, including some sustainability indexes. As highlighted in Table 1, the literature primarily focuses on the static allocation of improvements, with only one work considering budget levels, and none evaluating sustainability indexes related to improvement allocation.

This paper's research addresses the limitations of the existing literature by proposing a mathematical model for dynamically allocating improvements to the workstations of a flow line. Subsequently, extensive numerical results are provided, extending the analysis beyond the literature's scope to include bottleneck numbers, different levels of processing time increases, and two budget levels. The evaluation also incorporates total idle time as a measure of the flow line's energy consumption, which the allocation mod-

Table 1. Classification of the literature review

	Single machine	Flow line	Job-shop	Parameters	Sim.	Dynamic allocation	Budget level	Sustainability
[10]		X		Setup, MTBF, MTTR, process time variability, defect rate	X			
[11]		X		Setup, MTBF, MTTR, process time variability, defect rate	X			
[12]	X			MTTR, setup	X			
[14]		X		arrival and process time variability, defect rate, MTBF, MTTR, setup time.	X			
[13]		X		arrival and process time variability, defect rate, MTBF, MTTR, setup time.	X			
[15]			X	arrival and process time variability, defect rate, MTBF, MTTR, setup time.	X			
[16]		X		arrival and process time variability, defect rate, MTBF, MTTR, setup time.	X	X		
[17]		X		arrival and process time variability, defect rate, MTBF, MTTR, setup time.	X	X		
[18]		X		MTBF, MTTR,	X		X	
[19]		X		MTBF, MTTR,				
[20]		X		Setup, MTBF	X			
[21]		X		mean processing time and standard deviation	X			
[22]			X	mean processing time, MTBF, MTTR, setup time.	X			
[23]		X		layout	X	X		
[24]		X		mean processing time, MTBF, MTTR	X	X		
This paper		X		Setup, MTBF, MTTR, process time variability, defect rate	X	X	X	X

el aims to reduce. The original contribution of this research concerns the dynamical allocation of the improvements that is able to handle the fluctuations of the manufacturing system and include the energy consumption to improve the sustainable issue.

3. Model development

The improvement policies focused on a flow line where each workstation i processes the items with the same process time pt_i, except for a bottleneck workstation that works with a higher process time pt_b. Three areas of improvement concern the flow line:

- Setup time, which depends on various factors, such as changing tools in the workstation.
- The workstations are characterised by an average defect rate.
- Failures with Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) occur for each workstation of the flow line.

Then, four parameters can be modified by the introduction of improvement policies. Specifically, the reduction of the setup time, the reduction of defect rate, the reduction of MTTR and the increasing of MTBF. A budget is considered available for improvement, which can be allocated to the workstations for each parameter. The two policies used as benchmarks are proposed in Godinho Filho and Utiyama (2015). The first benchmark is the distributed policy, which allocates the budget of improvements equally on the workstation of the flow line for each parameter to improve (see Figure 1).

The second benchmark is the centralized policy that concentrates improvements solely on the bottleneck workstation of the flow line for all parameters to improve (see Figure 2). In cases where the flow line has more than one bottleneck, the improvements are distributed equally among the bottlenecks.

The two benchmark models are static policies: the distributed policy always allocates improvements uniformly among the stations, while the centralized policy remains static when the bottleneck is detected.

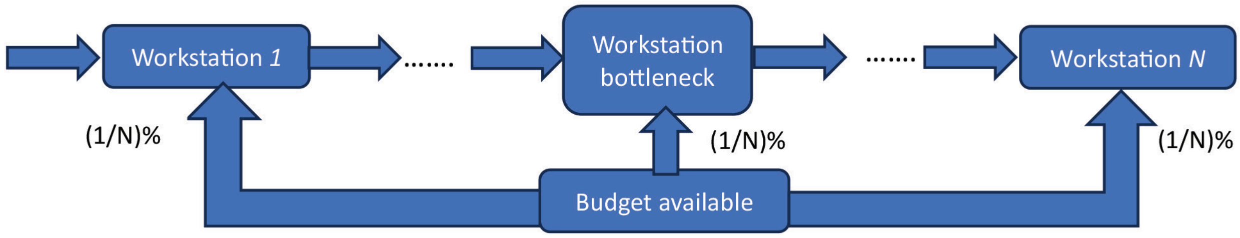


Figure 1. Distributed policy

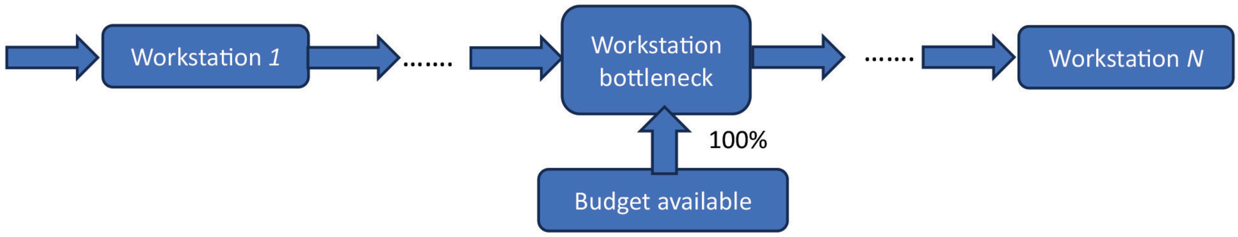


Figure 2. Centralized policy

3.1 The proposed improvement policy

The proposed policy dynamically allocates improvements to the stations and evaluates the enhancement for each considered parameter. The notation used is described in Table 2.

The parameters of the areas of improvement are defined as follows:

- K=1 is the setup;
- K=2 is the scraps;
- K=3 is the MTTR;
- K=4 is the MTBF.

The model is based on the computation of a cycle time for each workstation as shown in equation 1:

$$TC_i = \left(PT_i + Setup_i * (1 - impr_{1,i}) + \frac{MTTR_i * (1 - impr_{3,i})}{MTBF_i * (1 + impr_{4,i})} * PT_i\right) * \left(\frac{1}{1 - (Scraps_i * (1 - impr_{2,i}))}\right) \quad (1)$$

The cycle time computation considers the possible improvements of the parameters studied on each workstation that composes the flow line. For each parameter is evaluated the possible improvement of the cycle time.

Table 2. Notations and definition used in the study

Notation	Definition
Indices	
i	It is the index of the station i=1,..,I
k	It is the index of the parameters to improve k=1,..,K
Parameters	
PT_i	It is the processing time of the workstation *i*
$Setup_i$	It is the setup time of the workstation *i*, considered as the average setup time for unit of product
$MTBF_i$	It is the Mean Time Between Failures of the workstation *i*
$MTTR_i$	It is the Mean Time To Repair of the workstation *i*
$Scraps_i$	It is the average percentage of scraps for the workstation *i*
$Budget_k$	It is the budget to improve the parameter of the area *k*
Decision variables	
$impr_{ki}$	It is the value of improvement allocated to the workstation *i* for the area *k*
Tc_i	It is the cycle time of the workstation *i*

The mathematical model to allocate the improvements is the following.

$$Minimize \max_i TC_i \quad (2)$$

Subject to:

$$\sum_{i=1}^{I} impr_{k,i} \leq Budget_k \; \forall k \quad (3)$$

$Impr_{k,i}$ are integer positive

The objective function (expression 2) aims to minimize the cycle time of the flow line considering the higher cycle time of the stations. Constraint 3 ensures that the budget assigned to each station in each area is under the budget available for the improvement program. Improvements are constrained to integers to minimize fractional allocation. The mathematical model can dynamically allocate improvements, considering the operating conditions of each workstation, with limited computational complexity. This enables the activation of the model when operational conditions change.

4. Experiments and numerical results

The numerical results were obtained by considering 7 factors, each with two levels: Low (L) and High (H). The factors considered are: MTBF, MTTR, setup, defective rate, number of bottlenecks (bottleneck no.) in the flow line, the percentage increment of the processing time of the bottleneck (bottleneck %), and the level of budget available. The combination of all factors results in 128 experimental classes, which were conducted for the two benchmarks and the proposed policy, totaling 384 cases. Annex 1 reports the 128 experimental classes of the combinations of MTBF, MTTR, setup, defective rate, bottleneck number, bottleneck percentage and budget available for the simulation tests.

The flow line consists of 6 workstations (i=6) with the same factors except the processing time of the bottleneck. The processing time of the station PT_i=10 minutes, while the bottleneck has an increase of the processing time as shown the table 3 (bottleneck %). Table 3 reports the values for the two levels of each factor studied. The mathematical model (Section 3.1) for each experimental class is solved using Lingo® package.

The performance measures investigated with the allocation of improvement policies are as follows:

- The efficiency of the flow line considered the ratio between the cycle time of the experimental classes and the ideal cycle time of the flow line. This index evaluates the throughput rate of the flow line.
- The total idle time of the flow line considering the idle time of each workstation that composes the flow line. This index evaluates the idle time of the workstations that impacts on the energy consumption.
- The Coefficient Variation (CV) of the improvement allocations to evaluate the uniformity among the workstations of the flow line. This index evaluates how the improvement allocations is distributed among the workstations with higher complexity.

Table 4 presents the ANOVA analysis for the efficiency performance of the flow line, considering the comparison with distributed and centralized policies. The comparison with the distributed policy highlights how each factor considered affects the superior results of the proposed policy. In contrast, the comparison with the centralized policy shows that improvements are not affected by the factors: scraps, bottleneck number, and the available budget.

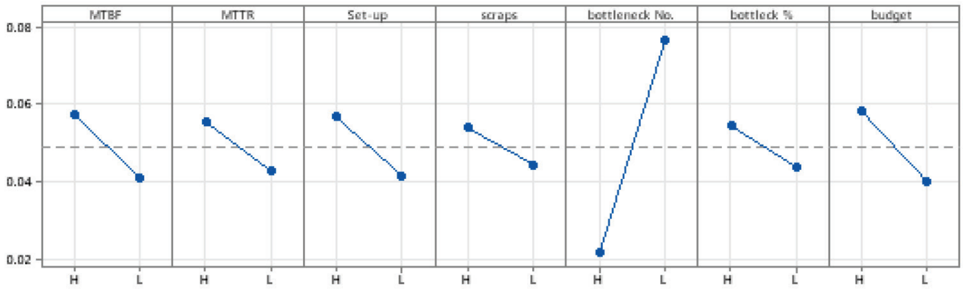
Figure 3 presents the main effects analysis of the proposed policy compared to the distributed and centralized policies. The average improvement with the proposed policy is approximately 4.9% compared to the distributed policy, whereas the improvement is notably lower compared to the centralized policy. The proposed policy performs better when all parameters are at the high level, except for the number of bottlenecks. The flow line efficiency obtained by the proposed model is the same of the centralized policy and the improvement allocation works better when the bottleneck number is lower.

Table 3. Base parameters value

level	MTBF [Minutes]	MTTR [Minutes]	Setup [minutes]	defect rate	bottleneck no.	bottleneck %	Budget available
L	500	5	0.5	1%	1	10%	50%
H	100	15	1.5	5%	3	30%	90%

Table 4. Flow line efficiency ANOVA analysis

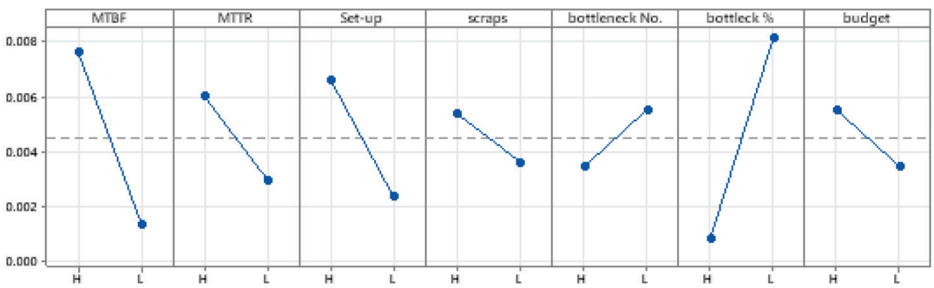
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Proposed model vs distributed policy					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
MTBF	1	0.008747	0.008747	36.17	0.000
MTTR	1	0.005135	0.005135	21.23	0.000
Set-up	1	0.007184	0.007184	29.70	0.000
defect rate	1	0.002797	0.002797	11.56	0.001
bottleneck No.	1	0.096608	0.096608	399.45	0.000
bottleck %	1	0.003554	0.003554	14.70	0.000
budget	1	0.010591	0.010591	43.79	0.000
Error	120	0.029022	0.000242		
Total	127	0.163636			
Proposed model vs centralized policy					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
MTBF	1	0.001228	0.001228	15.27	0.000
MTTR	1	0.000290	0.000290	3.61	0.060
Set-up	1	0.000577	0.000577	7.18	0.008
defect rate	1	0.000099	0.000099	1.23	0.269
bottleneck No.	1	0.000137	0.000137	1.71	0.194
bottleck %	1	0.001686	0.001686	20.97	0.000
budget	1	0.000133	0.000133	1.66	0.200
Error	120	0.009649	0.000080		
Total	127	0.013801			



3.a Main effects proposed mode vs distributed policy

efficiency=**0.04918** + 0.00827 MTBF_H - 0.00827 MTBF_L + 0.00633 MTTR_H - 0.00633 MTTR_L+ 0.00749 Set-up_H - 0.00749 Set-up_L + 0.00467 scraps_H - 0.00467 scraps_L- 0.02747 bottleneck No._H + 0.02747 bottleneck No._L + 0.00527 bottleck %_H - 0.00527 bottleck %_L + 0.00910 budget_H - 0.00910 budget_L

3.b regression equation proposed mode vs distributed policy



3.c Main effects proposed mode vs centralized policy

efficiency=**0.004483** + 0.003097 MTBF_H - 0.003097 MTBF_L + 0.001506 MTTR_H - 0.001506 MTTR_L+ 0.002123 Set-up_H - 0.002123 Set-up_L + 0.000880 scraps_H - 0.000880 scraps_L - 0.001036 bottleneck No._H + 0.001036 bottleneck No._L - 0.003630 bottleck %_H + 0.003630 bottleck %_L + 0.001020 budget_H - 0.001020 budget_L

3.d regression equation proposed mode vs centralized policy

Figure 3. Efficiency main effects analysis

Table 5 presents the ANOVA analysis for the idle performance of the flow line, considering the comparison with distributed and centralized policies. The improvement in this performance compared to the distributed policy is influenced by each of the factors studied. The comparison with the centralized policy highlights that only the MTTR factor does not affect the improvement of this performance index.

Figure 4 presents the main effects analysis of the proposed policy compared to the distributed and centralized policies regarding the reduction of idle time. The average improvement with the proposed policy is approximately 54% compared to the distributed policy and about 22% compared to the centralized policy. The proposed policy performs better when all parameters are at a high level, except for the number of bottlenecks and the increase in the processing time of the bottleneck. The proposed policy has a significant impact on reducing idle time, affecting energy consumption when workstations are in the idle state. This analysis highlights that the proposed model performs better for the reduction of idle time and the energy consumption of the line.

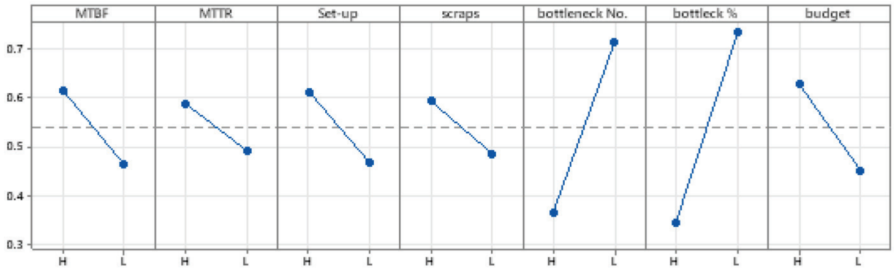
Table 6 presents the ANOVA analysis for the Coefficient of Variation (CV) of the improvement allocation. The distributed policy exhibits a perfectly uniform distribution. The CV of the proposed policy is influenced by the factors of Setup, bottleneck number, processing time increase, and available budget. The CV of the centralized policy is affected only by the number of bottlenecks.

Figure 5 shows the main effects on the CV index for the proposed and centralized policies. The average CV of the proposed policy is slightly higher of the centralized about 6% (1.8954 vs 1.77359). The CV of the proposed policy is characterized by higher fluctuations of the centralized policy. This means that the proposed model allocates the improvements with higher fragmentation of the benchmark models.

From the above results, the following main conclusions can be drawn. The centralized policy, as indicated in the literature, results in a better throughput rate than the distributed policy. The proposed policy achieves similar throughput rate results to the centralized policy, with slightly better outcomes in some tested cases. The primary advantage of the proposed policy, compared to both the distributed and centralized policies, lies in the reduction of idle time. This improvement is significant for reducing the energy consumption of machines in the idle state. The main advantage of the distributed policy is its fixed and uniform distribution of improvements to all workstations for all parameters. The proposed policy is characterized by a Coefficient of Variation of the improvement allocation that is closer to the centralized policy. The introduction of the proposed model can improve significantly the reduction of the total energy consumption of the flow line compared to the models proposed in the literature.

Table 5. Flow line idle time ANOVA analysis

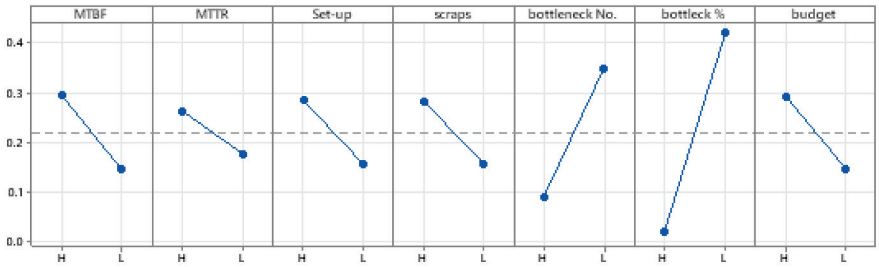
Proposed model vs distributed policy					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
MTBF	1	0.7237	0.72374	58.04	0.000
MTTR	1	0.2963	0.29629	23.76	0.000
Set-up	1	0.6736	0.67357	54.02	0.000
defect rate	1	0.3613	0.36135	28.98	0.000
bottleneck No.	1	3.7669	3.76686	302.10	0.000
bottleck %	1	4.7607	4.76066	381.80	0.000
budget	1	0.9673	0.96728	77.58	0.000
Error	120	1.4963	0.01247		
Total	127	13.0460			
Proposed model vs centralized policy					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
MTBF	1	0.7117	0.71165	9.02	0.003
MTTR	1	0.2416	0.24156	3.06	0.083
Set-up	1	0.5250	0.52495	6.65	0.011
defect rate	1	0.5102	0.51023	6.47	0.012
bottleneck No.	1	2.1157	2.11568	26.82	0.000
bottleck %	1	5.0593	5.05930	64.14	0.000
budget	1	0.6780	0.67797	8.59	0.004
Error	120	9.4660	0.07888		
Total	127	19.3073			



4.a Main effects proposed mode vs distributed policy

time=**0.53834** + 0.07519 MTBF_H - 0.07519 MTBF_L + 0.04811 MTTR_H - 0.04811 MTTR_L+ 0.07254 Set-up_H - 0.07254 Set-up_L + 0.05313 scraps_H - 0.05313 scraps_L- 0.17155 bottleneck No._H + 0.17155 bottleneck No._L - 0.19285 bottleck %_H+ 0.19285 bottleck %_L + 0.08693 budget_H - 0.08693 budget_L

4.b regression equation proposed mode vs distributed policy



4.c Main effects proposed mode vs centralized policy

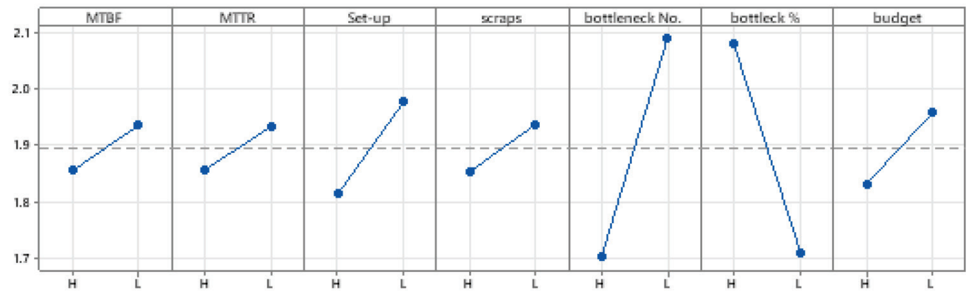
time=**0.2190** + 0.0746 MTBF_H - 0.0746 MTBF_L + 0.0434 MTTR_H - 0.0434 MTTR_L+ 0.0640 Set-up_H - 0.0640 Set-up_L + 0.0631 scraps_H - 0.0631 scraps_L- 0.1286 bottleneck No._H + 0.1286 bottleneck No._L - 0.1988 bottleck %_H + 0.1988 bottleck %_L + 0.0728 budget_H - 0.0728 budget_L

4.d regression equation proposed mode vs centralized policy

Figure 4. Idle time main effects analysis

Table 6. Flow line CV improvements time ANOVA analysis

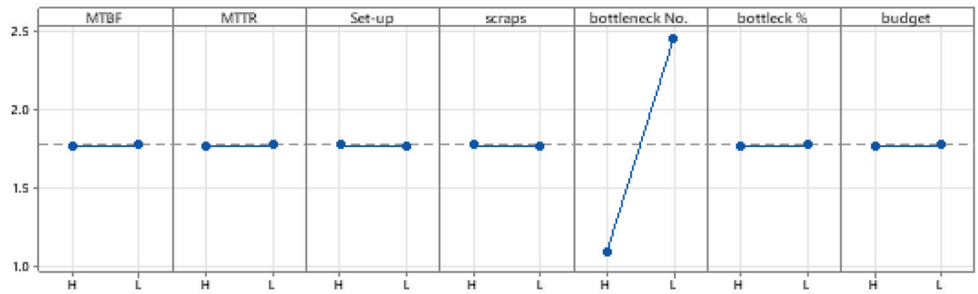
		CV Proposed model			
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
MTBF	1	0.2084	0.20836	2.46	0.119
MTTR	1	0.1928	0.19280	2.28	0.134
Set-up	1	0.8540	0.85399	10.09	0.002
defect rate	1	0.2263	0.22631	2.67	0.105
bottleneck No.	1	4.7694	4.76942	56.35	0.000
bottleck %	1	4.3913	4.39126	51.88	0.000
budget	1	0.5065	0.50652	5.98	0.016
Error	120	10.1576	0.08465		
Total	127	21.3062			
		CV centralized policy			
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
MTBF	1	0.0001	0.0001	1.00	0.319
MTTR	1	0.0001	0.0001	1.00	0.319
Set-up	1	0.0001	0.0001	1.00	0.319
defect rate	1	0.0001	0.0001	1.00	0.319
bottleneck No.	1	58.7618	58.7618	522630.91	0.000
bottleck %	1	0.0001	0.0001	1.00	0.319
budget	1	0.0001	0.0001	0.93	0.337
Error	120	0.0135	0.0001		
Total	127	58.7759			



5.a Main effects CV index proposed policy

CV=**1.8954** - 0.0403 MTBF_H + 0.0403 MTBF_L - 0.0388 MTTR_H + 0.0388 MTTR_L- 0.0817 Set-up_H + 0.0817 Set-up_L - 0.0420 scraps_H + 0.0420 scraps_L- 0.1930 bottleneck No._H + 0.1930 bottleneck No._L + 0.1852 bottleck %_H- 0.1852 bottleck %_L - 0.0629 budget_H + 0.0629 budget_L

5.b regression equation CV proposed policy



5.c Main effects CV index centralized policy

CV=**1.77359** - 0.000937 MTBF_H + 0.000937 MTBF_L - 0.000938 MTTR_H + 0.000938 MTTR_L+ 0.000938 Set-up_H - 0.000938 Set-up_L + 0.000938 scraps_H - 0.000938 scraps_L- 0.677552 bottleneck No._H + 0.677552 bottleneck No._L - 0.000938 bottleck %_H+ 0.000938 bottleck %_L - 0.000904 budget_H + 0.000904 budget_L

5.d regression equation CV index centralized policy

Figure 5. CV improvements main effects analysis

5. Conclusions and future development

This research proposes a dynamic allocation of improvement programs based on a simplified mathematical model supported by a throughput rate forecast computation. The proposed model is evaluated through a comparison with two policies proposed in the literature: distributed and centralized. The experiments consist of 128 cases, considering the parameters of MTBF, MTTR, setup, scraps, bottleneck numbers, processing time of bottlenecks, and budget available. The original contribution lies in the broader range of parameters studied and the evaluation of the idle time of the flow line. Idle time is significant for assessing energy consumption to enhance the sustainability of the manufacturing system. The main findings of the research are as follows:

- The centralized model outperforms the distributed approach in the 128 tested cases. This reaffirms the findings of key works in the literature that focused on a lower number of parameters.
- The proposed approach yields a throughput rate closer to the centralized model, with slight improvements in some cases.
- The primary advantage of the proposed policy is a significant reduction in idle time compared to the distributed and centralized policies. The proposed model enables a reduction of approximately 22% (compared to the centralized model) in idle time, leading to reduced energy consumption dependent on the energy consumed by the workstation in the idle state.
- The evaluation of the Coefficient of Variation of the improvement allocations indicates that the centralized and proposed models are very similar. This underscores the main benefit of the distributed approach, which has a fixed and uniform distribution of improvement allocations, making it a simpler policy to implement.

Then, it responds to the first research question asked: *Can the proposed allocation model improve the performance of the flow line compared to the benchmark models proposed in the literature?* The numerical results show how the proposed approach leads to the same throughput rate of the centralized policy, while is significantly better than the distributed policy. The second answer to the research question asks: *Can the proposed allocation model reduce the idle state of workstations without impacting manufacturing performance measures?* The evaluation of the total idle time shows how the proposed model enables a drastic reduction of idle time. Then, the proposed model with the same throughput rate of the centralized policy reduces the total idle time, and the related energy consumption, of about 22%.

The managerial implication concerns the information provided to the devisor maker that can select the more opportune improvement policy considering some significant indicators. The importance of a stable and simpler policy leads to choosing the distributed policy evaluation the efficiency loose. If the flow line is characterized by a higher energy consumption in the idle state, the proposed allows to reduce this energy with the same throughout rate of the centralized policy. The centralized approach can be the opportune choice when the throughput rate is the only relevant indicator because is a policy simpler than the proposed model.

Further research concerns the introduction of the costs in the mathematical model proposed to link the improvement allocation to the costs of the parameters to improve and the energy costs that is the main benefit of the proposed model. Moreover, the proposed will be studied in dynamic conditions with the allocation and re-allocation of the improvements when the manufacturing conditions change.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] P. Pande, R. P. Neuman, R. R. Cavanagh, The Six Sigma Way: How GE, Motorola and Other Top companies are Honing their Performance. New York: McGraw-Hill, 2000.

[2] N. Bhuiyan, A. Baghel, "An overview of continuous improvement: from the past to the present," Management Decision, vol. 43, no. 5, pp. 761-771, 2005, doi: 10.1108/00251740510597761.

[3] E. Goldratt, J. Cox, The goal: excellence in manufacturing. North River Press, Croton-onHudson, 1984.

[4] J. P. Womack, D. T. Jones, D. Ross, The machine that changed the world. Harper Perennial, New York, 1990.

[5] M. Godinho Filho, M.H.R. Utiyama, (2015). "Comparing different strategies for the allocation of improvement programmes in a flow shop environment," The International Journal of Advanced Manufacturing Technology, vol. 77, no. 5-8, pp. 1365-1385, 2015, doi: 10.1007/s00170-014-6553-5.

[6] S. Shingo, Sistema de troca rápida de ferramenta: uma revolução nos sistemas produtivos, Bookman, Porto Alegre, pp. 327, 2003.

[7] W.J. Hopp, M.L. Spearman, Factory Physics: Foundations of Manufacturing Management, Irwin, Nova Iorque, pp. 698, 2001.

[8] S. Hu, F. Liu, Y. He, T.Hu, "An on-line approach for energy efficiency monitoring of machine tools," Journal of Cleaner Production, vol. 27, pp. 133-140, 2012, doi: 10.1016/j.jclepro.2012.01.013.

[9] D. Kordonowy, A power assessment of machining tools. BSc thesis, Massachusetts Institute of Technology, Massachusetts, USA, 2003.

[10] M. G. Godinho Filho, R. Uzsoy, "The effect of shop floor continuous improvement programs on lot size-cycle time relationship for a multi- product single-machine environment", International Journal of Advanced Manufacturing Technology, Vol. 52, Nos. 5–8, pp.669–681, 2011, doi: 10.1007/s00170-010-2770-8.

[11] M. G. Godinho Filho, "Effect of lot-size reduction and continuous improvement programs on work in process and utilization: a study for single-machine and flow-shop environments", International Journal of Logistic Research and Applications, Vol. 15, No. 5, pp.285–302, 2012, doi: 10.1080/13675567.2012.741222.

[12] M. G. Godinho Filho, R. Uzsoy, "The impact of simultaneous continuous improvement in set up time and repair time on manufacturing cycle times under uncertain conditions", International Journal of Production Research, Vol. 51, No. 2, pp.447–464, 2012, doi: 10.1080/00207543.2011.652261.

[13] M. G. Godinho Filho, M. H. R. Utiyama, "Comparing different strategies for the allocation of improvement programmes in a flow shop environment", The International Journal of Advanced Manufacturing Technology, Vol. 77, No. 5–8, pp. 1365–1385, 2015, doi: 10.1007/s00170-014-6553-5.

[14] M. G. Godinho Filho, R. Uzsoy, "Assessing the impact of alternative continuous improvement programs in a flow shop using system dynamics", International Journal of Production Research, Vol. 52, No. 10, pp. 3014–3031, 2014, doi: 10.1080/00207543.2013.860249.

[15] P. Renna, "Allocation improvement policies to reduce process time based on workload evaluation in job shop manufacturing systems," International Journal of Industrial Engineering Computations, vol. 8, no. 3, pp. 373-384, 2017, doi: 10.5267/j.ijiec.2016.12.001.

[16] P. Renna, "Evaluation of improvement programmes in a job-shop context by simulation models," International Journal of Services and Operations Management, vol. 34, no. 2, pp. 241-258, 2019, doi: 10.1504/IJSOM.2019.103062.

[17] P. Renna and M. Ambrico, "The allocation of improvement programs in a flow shop for single and multi-products: a simulation assessment," Int. J. Agile Systems and Management, Vol. 12, No. 3, pp.228–244, 2019, doi: 10.1504/IJASM.2019.10022795.

[18] M. H. R. Utiyama, F. C. Correia, and D. H. Alliprandini, "Allocation of improvement strategies in a flow shop

with two capacity constrained resources," Int J Oper Quant Manag, vol. 26, no. 2, pp. 79–93, 2020, doi: 10.46970/2020.26.2.1.

[19] K. Wu, M. Zheng, and Y. Shen, "A generalization of the Theory of Constraints: choosing the optimal improvement option with consideration of variability and costs," IISE Transactions, vol. 52, no. 3, pp. 276-287, 2020, doi: 10.1080/24725854.2019.1632503.

[20] M. H. R. Utiyama, M. Godinho Filho, and P. C. Oprime, "An alternative for improving setup times and time between failures aiming at manufacturing lead time reduction, " Prod. Eng. Res. Devel., vol. 15, pp. 651–665, 2021, doi: 10.1007/s11740-021-01048-0.

[21] H. Govoni, F. B. D. Souza, R. F. Castro, J. D. S. Rodrigues, and S. R. I. Pires, "Analysis of production resources improvement strategies in make-to-stock environments managed by the simplified drum-buffer-rope system," Gestão & Produção, vol. 28, no. 4, pp. e55, 2021, doi: 10.1590/1806-9649- 2021v28e55.

[22] M. Kumbhar, A.H.C. Ng, and S. Bandaru, "A digital twin based framework for detection, diagnosis, and improvement of throughput bottlenecks," Journal of Manufacturing Systems, vol. 66, pp. 92-106, 2023, doi.org: 10.1016/j.jmsy.2022.11.016.

[23] P. Grznár, N. Burganová, Š. Mozol, and L. Mozolová, "A Comprehensive Digital Model Approach for Adaptive Manufacturing Systems," Applied Science, vol. 13, 10706, 2023, doi: 10.3390/app131910706.

[24] M. C. Magnanini and T. Tolio, "A model-based Digital Twin to support responsive manufacturing systems," CIRP Annals, vol. 70, no. 1, pp. 353-356, 2021, doi: 10.1016/j.cirp.2021.04.043.

[25] M. Javaid, A. Haleem, R. P. Singh, and R. Suman, "Enabling flexible manufacturing system (FMS) through the applications of industry 4.0 technologies," Internet of Things and Cyber-Physical Systems, vol. 2, pp. 49-62, 2022, doi: 10.1016/j.iotcps.2022.05.005.

Annex 1. Experimental classes

EXP. No.	MTBF	MTTR	Setup	defective rate	bottleneck no.	Bottleneck %	Budget available
1	L	L	L	L	L	L	L
2	H	H	H	H	L	L	L
3	H	L	L	L	L	L	L
4	L	H	L	L	L	L	L
5	L	L	H	L	L	L	L
6	L	L	L	H	L	L	L
7	H	H	L	L	L	L	L
8	H	L	H	L	L	L	L
9	H	L	L	H	L	L	L
10	L	L	H	H	L	L	L
11	L	H	H	L	L	L	L
12	L	H	L	H	L	L	L
13	H	H	H	L	L	L	L
14	H	H	L	H	L	L	L
15	H	L	H	H	L	L	L
16	L	H	H	H	L	L	L
17	L	L	L	L	L	L	H
18	H	H	H	H	L	L	H
19	H	L	L	L	L	L	H
20	L	H	L	L	L	L	H
21	L	L	H	L	L	L	H
22	L	L	L	H	L	L	H
23	H	H	L	L	L	L	H
24	H	L	H	L	L	L	H
25	H	L	L	H	L	L	H
26	L	L	H	H	L	L	H
27	L	H	H	L	L	L	H
28	L	H	L	H	L	L	H
29	H	H	H	L	L	L	H
30	H	H	L	H	L	L	H
31	H	L	H	H	L	L	H
32	L	H	H	H	L	L	H

33	L	L	L	L	H	L	L
34	H	H	H	H	H	L	L
35	H	L	L	L	H	L	L
36	L	H	L	L	H	L	L
37	L	L	H	L	H	L	L
38	L	L	L	H	H	L	L
39	H	H	L	L	H	L	L
40	H	L	H	L	H	L	L
41	H	L	L	H	H	L	L
42	L	L	H	H	H	L	L
43	L	H	H	L	H	L	L
44	L	H	L	H	H	L	L
45	H	H	H	L	H	L	L
46	H	H	L	H	H	L	L
47	H	L	H	H	H	L	L
48	L	H	H	H	H	L	L
49	L	L	L	L	H	L	H
50	H	H	H	H	H	L	H
51	H	L	L	L	H	L	H
52	L	H	L	L	H	L	H
53	L	L	H	L	H	L	H
54	L	L	L	H	H	L	H
55	H	H	L	L	H	L	H
56	H	L	H	L	H	L	H
57	H	L	L	H	H	L	H
58	L	L	H	H	H	L	H
59	L	H	H	L	H	L	H
60	L	H	L	H	H	L	H
61	H	H	H	L	H	L	H
62	H	H	L	H	H	L	H
63	H	L	H	H	H	L	H
64	L	H	H	H	H	L	H
65	L	L	L	L	L	H	L
66	H	H	H	H	L	H	L
67	H	L	L	L	L	H	L
68	L	H	L	L	L	H	L
69	L	L	H	L	L	H	L
70	L	L	L	H	L	H	L
71	H	H	L	L	L	H	L
72	H	L	H	L	L	H	L
73	H	L	L	H	L	H	L
74	L	L	H	H	L	H	L
75	L	H	H	L	L	H	L
76	L	H	L	H	L	H	L
77	H	H	H	L	L	H	L
78	H	H	L	H	L	H	L
79	H	L	H	H	L	H	L
80	L	H	H	H	L	H	L
81	L	L	L	L	L	H	H
82	H	H	H	H	L	H	H
83	H	L	L	L	L	H	H

84	L	H	L	L	L	H	H
85	L	L	H	L	L	H	H
86	L	L	L	H	L	H	H
87	H	H	L	L	L	H	H
88	H	L	H	L	L	H	H
89	H	L	L	H	L	H	H
90	L	L	H	H	L	H	H
91	L	H	H	L	L	H	H
92	L	H	L	H	L	H	H
93	H	H	H	L	L	H	H
94	H	H	L	H	L	H	H
95	H	L	H	H	L	H	H
96	L	H	H	H	L	H	H
97	L	L	L	L	H	H	L
98	H	H	H	H	H	H	L
99	H	L	L	L	H	H	L
100	L	H	L	L	H	H	L
101	L	L	H	L	H	H	L
102	L	L	L	H	H	H	L
103	H	H	L	L	H	H	L
104	H	L	H	L	H	H	L
105	H	L	L	H	H	H	L
106	L	L	H	H	H	H	L
107	L	H	H	L	H	H	L
108	L	H	L	H	H	H	L
109	H	H	H	L	H	H	L
110	H	H	L	H	H	H	L
111	H	L	H	H	H	H	L
112	L	H	H	H	H	H	L
113	L	L	L	L	H	H	H
114	H	H	H	H	H	H	H
115	H	L	L	L	H	H	H
116	L	H	L	L	H	H	H
117	L	L	H	L	H	H	H
118	L	L	L	H	H	H	H
119	H	H	L	L	H	H	H
120	H	L	H	L	H	H	H
121	H	L	L	H	H	H	H
122	L	L	H	H	H	H	H
123	L	H	H	L	H	H	H
124	L	H	L	H	H	H	H
125	H	H	H	L	H	H	H
126	H	H	L	H	H	H	H
127	H	L	H	H	H	H	H
128	L	H	H	H	H	H	H