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Workload control order release with controllable processing time policies: an assessment by simulation

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ABSTRACT

Workload Control is used in manufacturing systems to obtain more predictable throughput times and accurate delivery dates. The models proposed in the literature are typically focused on machines with fixed processing time. This study, therefore, uses simulation to investigate the performance of the Workload Control method with a controllable processing time of the machines. This research proposes four models to support the decisions on the time to reconfigure the machines and the number of machines reconfigured. The time decision follows two strategies as periodic and continuous, while the machines reconfigured can be all or two considering the workload. The combinations of these strategies lead to four models that are tested in different conditions of reconfiguration times and the number of bottlenecks. The results suggest as the proposed models allow to improve delivery time performance and a more uniform distribution of workload among the machines of the manufacturing systems.

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1. Introduction and motivation

Among the production planning and control concept, Workload Control (WLC) emerging as suitable for Small and Medium Enterprises (SMEs) that work in a Make-To-Order system [1]. When the orders arrive, the jobs wait in a pre-shop pool, and they are released following order-release rules. Following this control of the order release, the performance measures of the shop floor are stabilized from the variation of the incoming orders [2]. The short-term decisions (the acceptance order is a medium-term decision) are the following: order release level [3], priority dispatching level, and workload computation. One of the main sources of competition is the continuous improvement of manufacturing firms.

At the shop floor level, the strategies proposed in the literature are the following: the improvements focused on the Capacity Constraint Resource (CCR) [4]; the distributive strategy allocates the efforts to all workstations on the production line [5]; a hybrid strategy that is a combination of the two previous strategies [6]. Some examples of improvement areas are the following: processing time, variability of the processing time, set-up time, mean time between failures, mean time to repair, and demand variability.

In this research, it is considered the area of the processing time related to the controllable process-

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ing time. The control of the processing time adapts the manufacturing system to the change in product mix, demand fluctuations, etc. The development of Industry 4.0 enables manufacturing systems for real-time tracking and monitoring [7, 8]. This allows controlling the manufacturing systems in real-time where the opportune decision support model to make decisions. Simulation model is a relevant technique to support and develop complex system such as the manufacturing systems based on Industry 4.0 paradigm [9,10].

The research proposed in this paper focuses on the workload control approach with the introduction of controllable processing time. The controllable processing time can be supported by investment in reconfigurable machines, material handling, tools, and other improvement investments.

The controllable processing time is supported by nonlinear mixed-integer programming formulation or heuristic algorithm as the genetic algorithm [10, 11] and that increases the computational complexity reducing the application in real industrial cases with more complex manufacturing systems.

The integration of the workload control and controllable processing time can be a valid and effective alternative to the models proposed in the literature reducing the computational complexity and facilitating the introduction in industrial cases.

A policy for the controllable processing time of the machines is proposed for the WLC system highlighting the potential improvements of the manufacturing system performance.

A simulation is proposed to asset the performance compared to the most typical WLC applied in the literature.

The remainder of this paper is organized as follows. Section 2 discusses the literature on workload control and controllable processing time and outlines the research questions that motivate our study. Section 3 describes the manufacturing system context, while the proposed models are presented in Section 4. The simulation model used to evaluate performance is then described in Section 5 before the results are presented in Section 6. Finally, conclusions, managerial implications, and future research directions are provided in Section 7.

2. Literature overview

This section provides a brief overview of the recent literature on WLC and controllable processing time models.

The first decision of the workload control (after the acceptation of the jobs) is the release of the jobs at the right moment. The performance of the workload control depends on this decision. The main strategies proposed in the literature are the periodic time intervals [13], the continuous release method that monitors when an operation is complete or a new job arrives at the shop [14] and mathematical models that include also the balancing problem of the manufacturing system [15].

The continuous release method has the better trade-off between results and computational complexity.

Based on the release method, the research evaluates the due date assignation considering forecasting system to maximize the on-time deliveries [16,17].

The computation of the workload has a crucial importance for the integration with the controllable processing time. Several works studied the workload computation starting from the classical corrected aggregate load approach [13]. Thürer et al. [18] evaluated two methods to compute aggregate workload; the corrected aggregate computation leads to better performance in all experiments conducted. This approach is static and does not take into account the real-time information about the manufacturing system. Renna [19] proposed a corrected workload computation based on the average utilization of the machines; this approach performs better for specific performance measures such as the percentage of parts in delay and the average time in the manufacturing system. Renna [20] developed a dynamic workload computation to handle the real-time information of the manufacturing system. The approach improves the performance, and it is robust under different conditions.

Some works studied the WLC in flow shops considering the buffer constraint [21] or the capacity adjustment in the job-shop context [22].

In this research, the classical aggregate load approach [13] because is easier to integrate with the controllable processing time.

The controllable processing time can be related to investment in machine, tools, material handling, workers training, etc. Then, the control of the processing time can be included in the improvement programme of manufacturing systems. In this context, some studies support the budget allocation to improve the production system, but at the managerial level and do not concern the shop floor level [23, 24].

A simulation model for scheduling the jobs considering the processing time-dependent on resource assignment was proposed by Moon et al. [25]. The results obtained show relevant improvements with the modified production schedule. Three policies of improvement allocation (centralized, distributed, and proportional) are proposed to focus the processing time reduction using the information derived from the workload control [26]. The simulation results can support the choice among the policies in determining manufacturing conditions. Lou et al. [27] and Meng et al. [28] proposed multi-objective models based on heuristic algorithms to minimize the makespan with controllable processing time. The processing time is controlled with additional resources for the operations.

Lout et al. [27] studied the multi-objective flexible job-shop scheduling problem with variable processing speeds aiming at minimizing the makespan and total energy consumption simultaneously.

Shioura et al. [29] addressed several scheduling problems with controllable processing time. The objective was to reduce the processing time minimizing the compression cost. The study is limited to identical parallel machines. Gao et al. [30] studied the reconfigurable manufacturing systems to minimize the total penalty for tardiness. They proposed a linear mathematical model and genetic algorithm that limit the application to small manufacturing system.

From the above review, it becomes evident that while there exists a broad literature on WLC, the controllable processing time was not considered in the case of workload control methods. The works on WLC considered the workstations with fixed processing time. Moreover, the controllable processing time was investigated in simplified manufacturing systems as single or identical parallel machines. Therefore, the workload control with controllable processing time can overcome the above limits with decision-making in real-time [31].

In response, this paper proposes decision-making models to support the controllable processing time in job shop controlled by WLC by first asking:

RQ1: What is the impact on the performance of controllable processing time combined with WLC method in job-shop?

This research addressed the problem of the time to modify the processing time by periodic and continuous review, while the workstations can be all (proportional method) or only two (dual method). The combination of these strategies leads to four possible decision-making models.

Therefore, the second research question asks:

RQ2: what is the best combination policy continuous/periodic with proportional/dual to support the reconfiguration of processing time activities?

A proper design of experiments with the simulation models will be used next to answer the above research questions. The numerical results seek to provide a guide to the manager to select the decision-making model in different conditions of reconfiguration times and the number of bottlenecks in the manufacturing system.

3. Proposed models

The manufacturing system to test the proposed models is the same investigated in previous works [11,29] and many studies afterward.

The manufacturing system is a job-hop that consists of six workstations (with one machine), and each machine performs one operation. The number of the operations with the related processing time and the due date is assigned to each job that enters the job shop. The works proposed in the literature considered an ordered sequence of the operations, in this work the routing sequence is completely randomized without a preferred order.

All jobs are accepted, and raw materials and tools are always available following several studies proposed in the literature [33, 34, 35, 36]. The Earliest Due Date priority sequencing rule manages the queue of the machines to reduce the jobs completer over the due date assigned.

The notation used is described in the following:

	Notation	Definition
Indices	M	It is the number of workcenter/machine that composes the manufacturing system
	m	It is the index of the machines $m=1,..,M$
	i	It is the index of the jobs in the pre-shop queue
Parameters	PT_{im}	It is the base processing time of the technological operation performed by the machine *m* of the part *i*
	WLnorm	It is the norm of the workload control mechanism
	DD_i	It is the due date assigned to the job *i*
	a_{im}	It is a binary value equal to 1, if the job i must visit the machine m, 0 otherwise
	Seq_{im}	It is the ordered sequence of the machine *m* for the job *i*

	Th	It is a Threshold used for the continuous strategy
	$Setup_m$	It is the setup time to reconfigure the machine for the modified processing time *m*
	PTp_m	It is the factor that determines the increasing/decreasing percentage of the processing time of the machine *m*
Computation	WL_m	Workload of the machine *m*

According the corrected aggregate load method [13], the potential workload is computed as shown in expression (1):

$$WL_m = WL_m + \sum_{m=1}^{M} \frac{PT_{im} * a_{im}}{Seq_{im}} \quad (1)$$

The potential workload computed is used to decide, if the job can be released in the manufacturing system. The job can be released in the manufacturing system, if the workload of each machine is lower than the workload norm *WLnorm*. If the job is released the workload computed as shown in expression (1) is updated for each workcenter.

When the job i leaves a machine, the workload of the machine is updated as shown in expression (2):

$$WL_m = WL_m - \frac{PT_{im}}{Seq_{im}} \quad (2)$$

The proposed models share the increase/decrease of the processing time among the machines like a budget available. Therefore, if a machine reduces the processing time another machine increases it keeping the sum of increasing/decreasing to 0. This approach can be related to several situations where limited resources are shared among the machines as the power that have to respect the peak power constraints, tools, or worker allocation. One example is described in Renna [37] where some machines can reduce the processing time by increasing the power and others increase the processing time by reducing the power under the peak power constraint; allocation of operations and their tools with controllable processing time to minimize the processing costs [38].

The proposed model is completely general, and the processing time can be modified by the power, tools, or allocation of the workers.

Two main decisions concern the develop element of the models: when the processing time changes (reconfiguration of the machines) and how to allocate the *"budget"* of the processing time among the machines.

The first decision follows two possible strategies:

- a periodic review with a fixed time (P); The periodic strategy works on a fixed period when the workload of the machines is evaluated, and then the decision about the processing time allocation is made.
- a continuous review where the processing time changes when a particular condition occurs (C). In this research, it is considered the difference between the higher and lower value of the workload as the condition to evaluate. When this difference is higher than a threshold (eq. 3), the processing time reconfiguration starts.

$$\max_m WL_m - \min_m WL_m > Th \quad (3)$$

The threshold *Th* is related to the *WLnorm* defined for the workload control of the manufacturing systems by a coefficient between 0 and 1 as shown in eq. 4:

$$Th = \alpha * WLnorm, \alpha \in [0,1] \quad (4)$$

Also, the second decision follows two strategies. In the first case, the processing time of all machines is modified (A); when the reconfiguration policy is performed, all the machines change the processing time. The processing time adapts proportionally to the workload by the following steps.

First, the total workload is computed as the sum of the workload of the machines (eq. 5):

$$WLtot = \sum_{m=1}^{M} WL_m \quad (5)$$

Then, a normalized index for each machine that takes into account the workload of the machine with the total workload (eq. 6).

$$WLp_m = \frac{WL_m}{WLtot} \quad (6)$$

A factor that defines the increasing/decreasing percentage of the processing time is the workload distribution. The value (1/M) is considered the normalized workload when the machines are equally loaded. If the normalized index of the machine is greater than 1/M, the factor PTp_m is lower than one (eq. 9), then the processing time reduces following eq. 7. Otherwise, if the normalized index of the machine is lower than 1/M, the factor PTp_m is greater than one (eq. 6), then the processing time reduces following eq. 6. Because the sum of the WLp_m is one, this assures that the increment and decrement are balanced.

$$PTp_m = 1 - (WLp_m - \frac{1}{M}) \quad (7)$$

$$PT_m = PTp_m * PT_{im} \quad (8)$$

In the second case, only two machines change the processing time (T). This approach leads to reduce the number of reconfigurations. The machines with the highest and lowest workload are calculated and determined (eq. 9 and 10). Then, it is computed the percentage reduction (eq. 9 and 11) and percentage increment (eq. 12 and 14) of the two machines.

$$WLp_{max} = \max_m WLp_m \quad (9)$$

$$WLp_{min} = \min_m WL_{pm} \quad (10)$$

$$PTp_{max} = 1 - (WLp_{max} - WLp_{min}) \quad (11)$$

$$PTp_{min} = 1 + (WLp_{max} - WLp_{min}) \quad (12)$$

$$PT_m(\max) = PTp_{max} * PT_{im} \quad (13)$$

$$PT_m(\min) = PTp_{min} * PT_{im} \quad (14)$$

Then, the combination of all strategies leads to obtaining four models to support the processing time changing of the manufacturing system: PA – PT - CA – CT.

All the strategies are characterized by a setup time ($Setup_m$) equal for all machines to reconfigure the processing time.

4. Simulation environment

The proposed model is compared to a benchmark with a classical workload control with fixed processing time, the main parameters are the same used in [39, 40]. The benchmark is the same used in literature to evaluate the effect of the proposed models with the workload control approach. Table 1 reports the characteristics of the basic manufacturing system tested. The processing time reported in table 1 is the base processing time before the actions of the model proposed.

The experimental classes (table 2) are 39, considering 12 combinations with three bottleneck cases and the benchmark for the three bottleneck cases. The simulation length is 25,000 hours. Each case is

Table 1. Models' characteristics

Number of machines	Characteristics		
	6 (1 bottleneck and 5 no-bottlenecks) [B1]	6 (2 bottleneck and 4 no-bottlenecks) [B2]	6 (3 bottleneck and 3 no-bottlenecks) [B3]
Inter-arrival	EXPO 0.642		
Number of operations	Discrete Uniform [1, 6]		
Due date	(Number of operations)*(total processing time)*Uniform [5, 10]		
Processing times no-bottlenecks	2-Erlang with mean 1		
Processing times bottlenecks	2-Erlang with mean 1.15 (utilization about 90 %)		

Table 2. Experimental Classes

Case No.	Review policy	Reconfiguration resources	$Setup_m$
1	Continuous	Proportional	2
2	Continuous	Proportional	1
3	Continuous	Proportional	0.5
4	Continuous	Dual	2
5	Continuous	Dual	1
6	Continuous	Dual	0.5
7	Periodic	Proportional	2
8	Periodic	Proportional	1
9	Periodic	Proportional	0.5
10	Periodic	Dual	2
11	Periodic	Dual	1
12	Periodic	Dual	0.5

simulated by modifying the workload norm (from 10 to 35 with a step of 1), the *Th* value for the continuous strategy (from 0.5 to 1 with a step of 0.1), and the periodic time for the periodic strategy (from 25 to 80 with a step of 1) to determine the best combination that minimizes the performance of tardy and lateness of the jobs. To determine the best combination of parameters each continuous class leads to 36 (workload norms)*6 (*Th* values)=216 sub-cases and 36 (workload norms)*56 (periodic parameter values)=2016 sub-cases. The range of the parameters is chosen with preliminary simulations. The three setup time values ($Setup_m$) are related to the base processing time (2-Erlang with mean 1) and are a greater value (two times the mean), as the base process time and lower the base process time.

For each experiment class and relative sub-cases, a statistical analysis is performed for terminating simulation case. The number of iterations of each simulation case is computed using the 95 % of confidence level and assure the 5 % confidence interval for each performance measure. This leads to thousands of iterations for each simulation case.

The simulations results are evaluated by the following performance measures:

- Jobs completed over the due date as a percentage of the total production [%];
- The average lateness of the jobs [unit time]
- Average throughput time of the jobs [unit time];
- average jobs in queue machine [number of jobs];
- Standard deviation of the machine queues;
- average utilization of the machines.
- Standard deviation of the average utilization of the machines.

5. Numerical results

Table 3 reports the best value of the parameters for each simulated case in terms of the workload norm (norm) and the parameter* is the value of α for cases 1-6 and the periodic time for cases 7-12.

The parameters *Th* assumes a stable value for cases 5 and 6 that is the continuous-dual model with medium and lower reconfiguration times. The same behavior can be observed for the optimal value of the periodic-dual model (Cases 10,11 and 12). Then, the approach *"dual"* is more robust to the parameter setting over the bottleneck changes. Generally, the optimal workload norm reduces when the reconfiguration time is lower.

Figure 1 reports the percentage difference of the proposed models compared to the benchmark for the throughput.

The periodic-dual model leads to the better values for this performance (cases 10, 11 and 12). The benefit is greater when the bottleneck changes from 1 to 3. The reconfiguration time has a low influence for cases 10,11 and 12; therefore, the periodic-dual model leads to better results with robustness. Another model competitive is the continuous-dual when the reconfiguration time is lower (case 6) and the periodic-dual with lower reconfiguration time (case 9). Generally, the reconfiguration of two machines is the better approach for the throughput.

Figure 2 reports the percentage difference of the proposed models compared to the benchmark for the throughput time.

The reduction of the throughput time is lower when the bottleneck is greater than 1, and the values are very similar for 2 and 3 bottlenecks. The better cases (6 and 12) concern the continuous and periodic

Table 3. Best parameters for each simulated case

best	1	2	3	4	5	6	7	8	9	10	11	12
						1 Bottleneck						
norm	30	25	15	14	12	10	29	15	15	23	25	27
parameter*	0.8	0.78	0.86	0.86	0.75	0.75	54	41	34	30	31	31
						2 Bottlenecks						
norm	30	33	15	12	11	11	25	10	12	25	26	25
parameter*	0.85	0.78	0.84	0.81	0.75	0.75	58	44	31	31	31	31
						3 Bottlenecks						
norm	33	25	14	12	13	11	25	11	11	27	25	28
parameter*	0.94	0.84	0.83	0.79	0.75	0.76	68	47	31	30	30	30

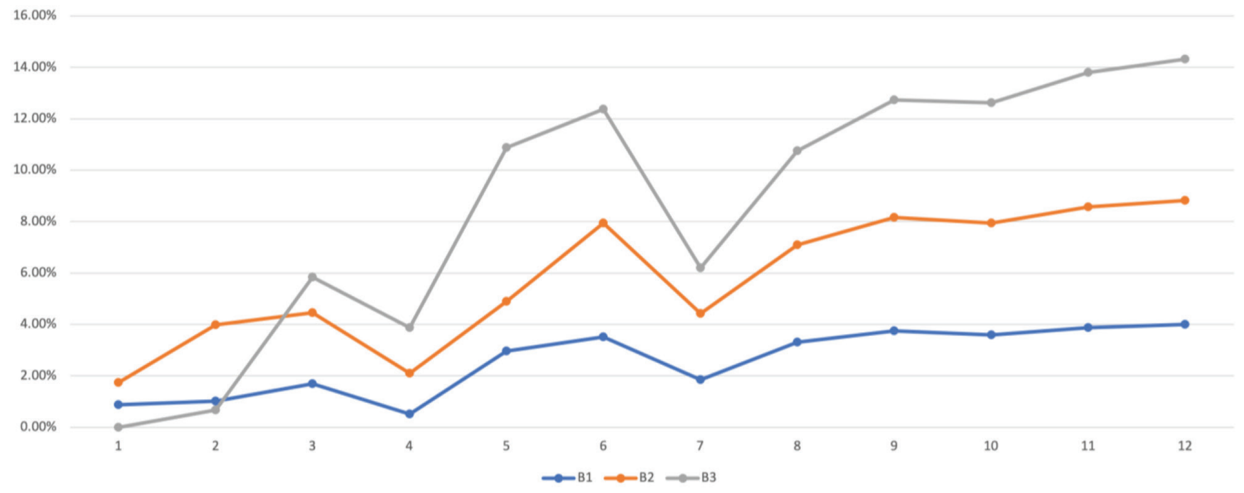

Figure 1. Throughput

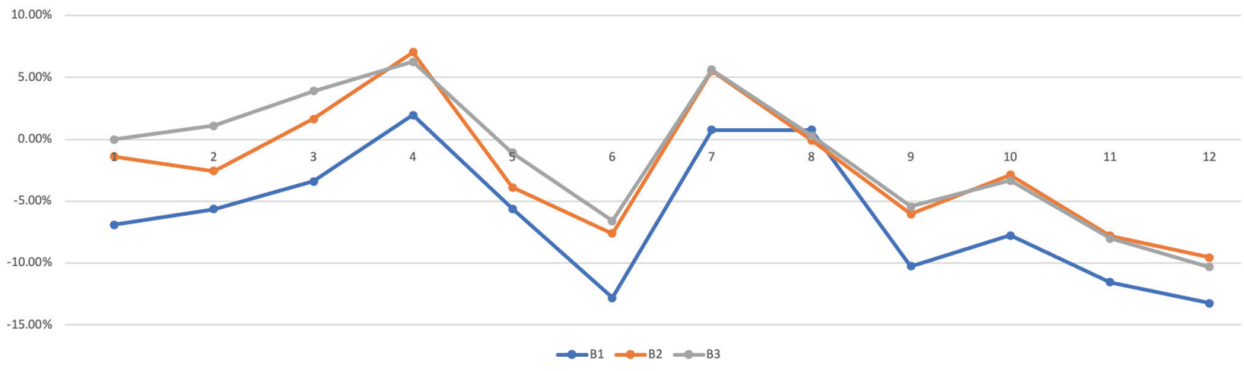

Figure 2. Throughput time

dual with lower reconfiguration time. This performance is more influenced from the reconfiguration time.

Figure 3 reports the percentage difference of the proposed models compared to the benchmark for the parts in delay.

The number of bottlenecks has a low influence on this performance. The better cases are the same determined by the previous performance measures (6, 10,11, and 12). The reduction obtained is very relevant (80%-90%) for the parts in delay. Moreover, average tardiness has the same behavior as this performance.

Figure 4 reports the percentage difference of the proposed models compared to the benchmark for the average utilisation of the workstations.

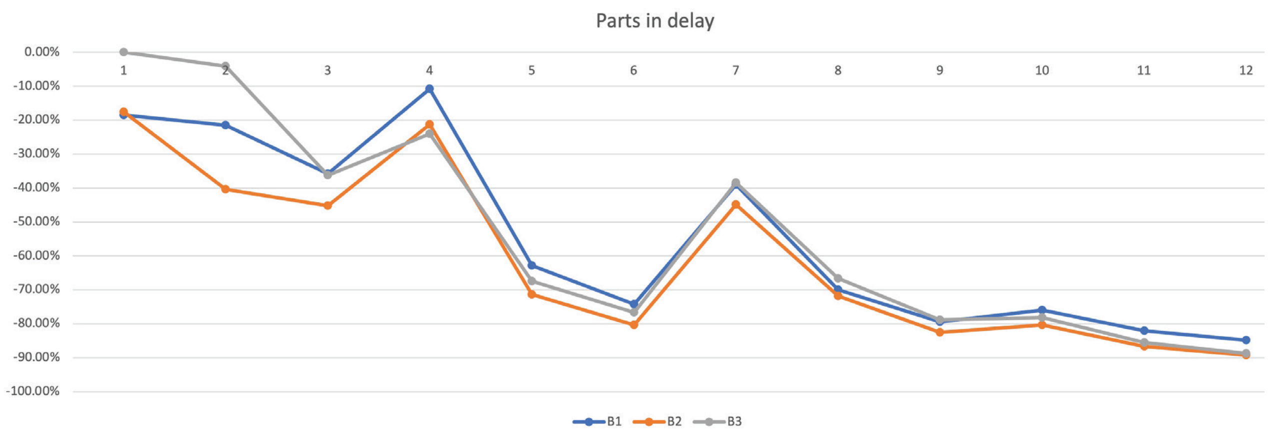

Figure 3. Parts in delay

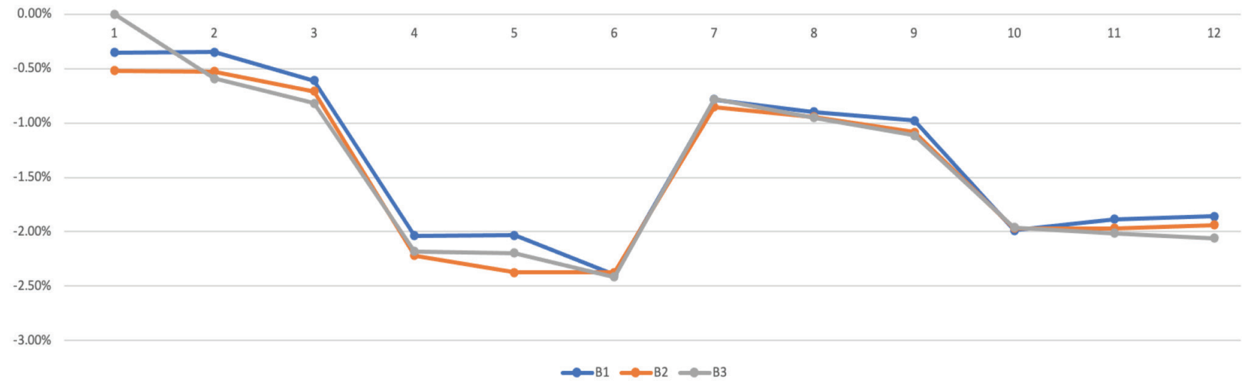

Figure 4. Average utilization

The number of bottlenecks has a low influence and the reduction is very limited to a maximum value of about 2.50%.

Figure 5 reports the percentage difference of the proposed models compared to the benchmark for the standard deviation of the average utilisation of the workstations. Bottleneck 1 and 3 lead to a better distribution of the utilization among the workstations, while the case with two bottlenecks reduces the benefit. The proposed models allow distributing the utilisation among the machines with higher uniformity.

Figure 6 reports the percentage difference of the proposed models compared to the benchmark for the average queue of the workstations. The reduction of the average queues is better from one bottleneck to three bottlenecks. A relevant impact is due to the reconfiguration time. Generally, the dual approaches are the better cases.

Figure 7 reports the percentage difference of the proposed models compared to the benchmark for the standard deviation of average queue of the workstations. The distribution of the queues is more uni-

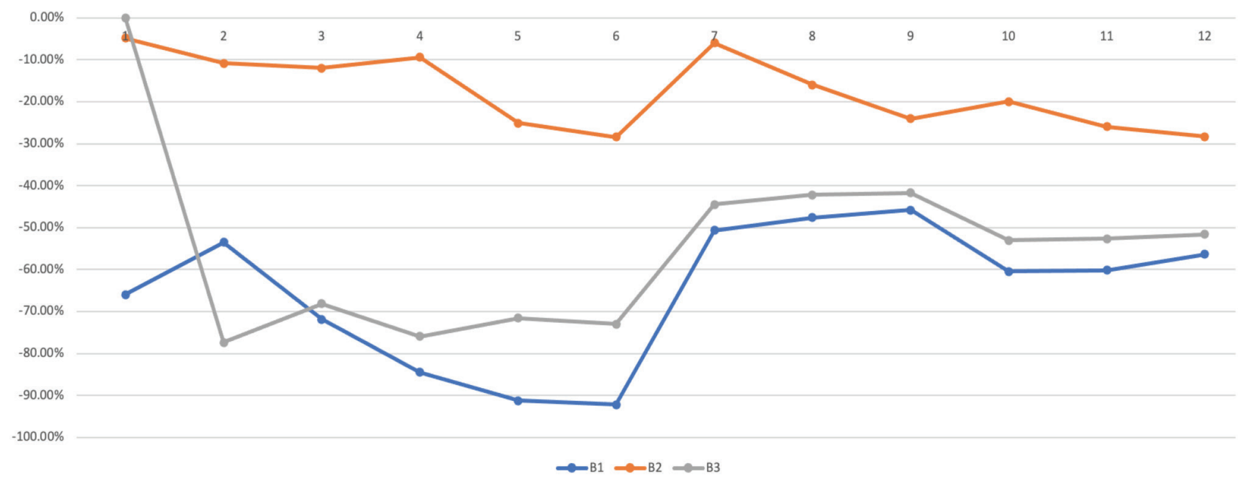

Figure 5. Standard deviation of the average utilization

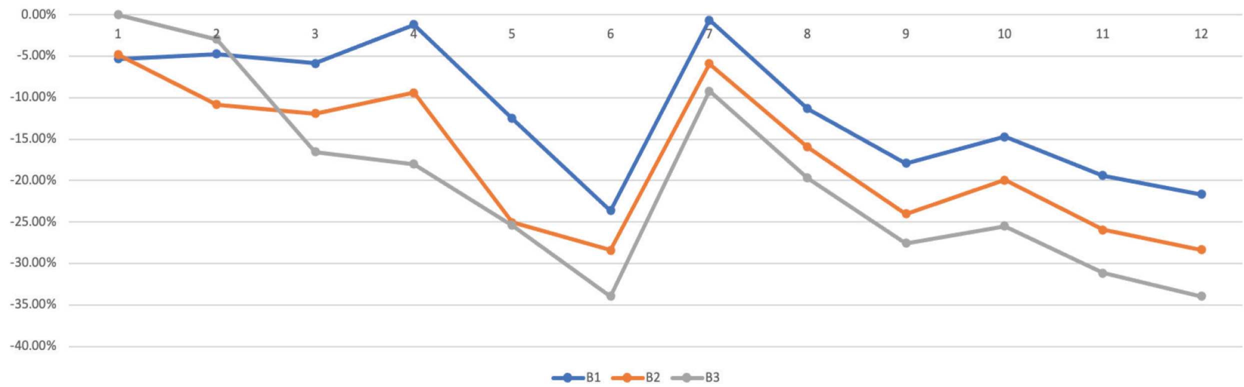

Figure 6. Queues

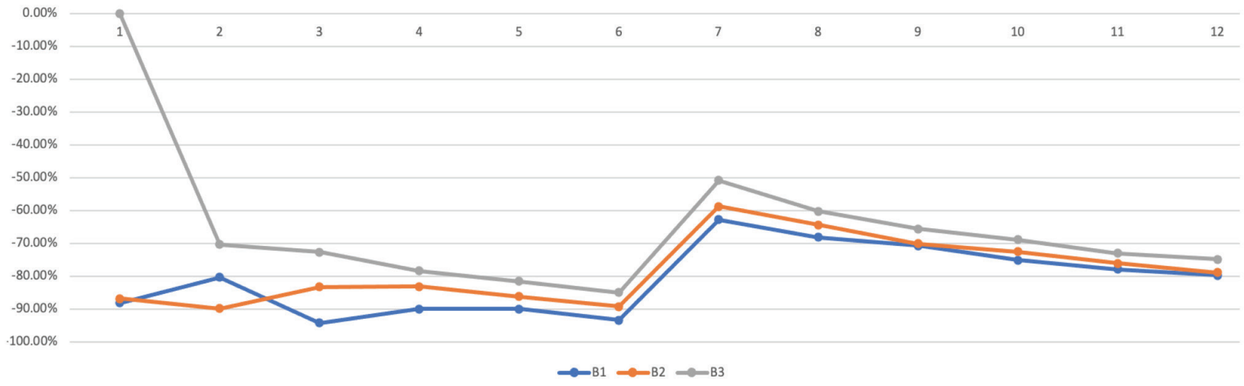

Figure 7. Standard deviation of the Queues

form for the great part of the cases. The bottleneck has a low influence on this measure.

Figure 8 and 9 reports the analysis of the reconfiguration activities that determines the costs of the models proposed. Figure 8 reports the number of reconfiguration activities of the manufacturing systems that is a fixed cost.

The better performance measures are obtained with 800 reconfiguration activities over the 25,000 hours simulated. Then, it is an average of a reconfiguration activity on 31 hours.

A relevant evaluation concerns the number of machines reconfiguration that is lower for the cases with dual approach (figure 9) that is reduces the costs to

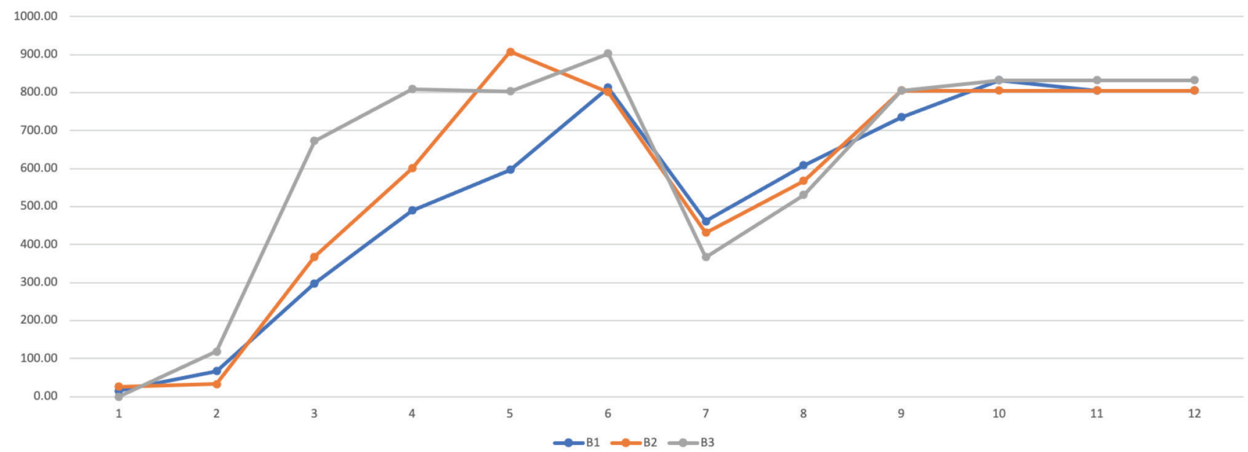

Figure 8. Number of reconfiguration activities

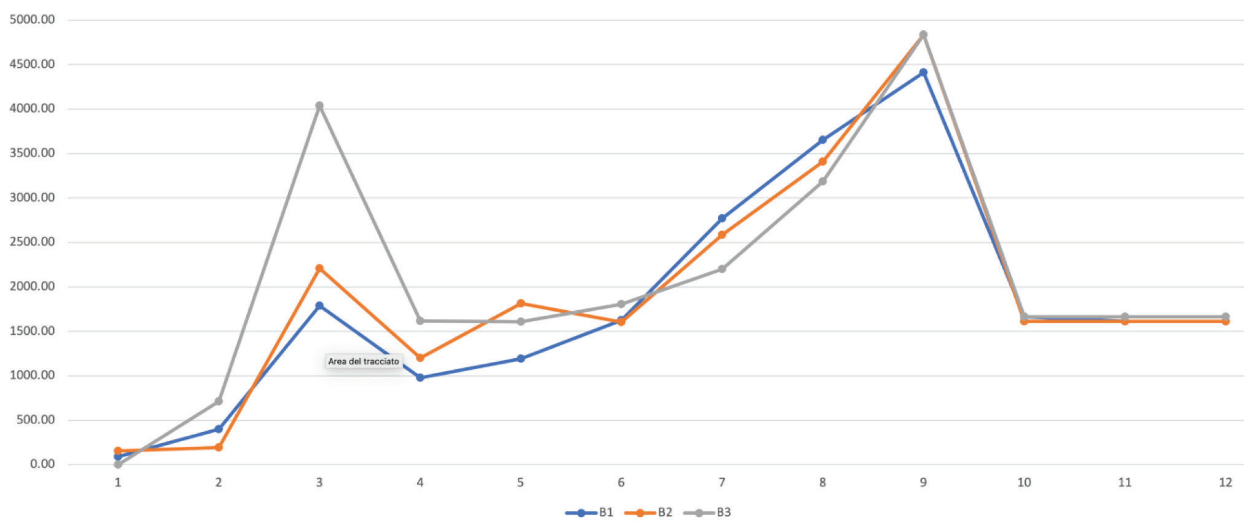

Figure 9. Number machines' reconfigurations

obtain the better performance compared the other models.

From the above results, the following issue can be reassumed:

- The models periodic-dual is the most promising approach to improve the main performance of the manufacturing systems. Moreover, this model allows to homogenize the utilization and the queue of the machines.
- The robustness of the improvements is confirmed considering the number of bottlenecks and the reconfiguration time.
- The improvements of the performance are subjected to a reconfiguration activity on about 31 hours, and the dual model allows to keep lower the number of machines reconfiguration. This is relevant for the evaluation of the costs of the models.

6. Conclusions and future development paths

To stay competitive in the global context, a strategic goal of manufacturing systems is to be able to response quickly to the market changes as new product introduction, demand and mix changes, etc. Workload Control is a production planning and control concept used to align demand and capacity. The reconfigurable machines are able to rapid change in its structure (hardware and software) to change functionality and production capacity as the processing time.

The research on Workload Control considered the machines as dedicated resources. This research studies the introduction of reconfigurable machines and how to reconfigure these machines under the workload control model. It is important to define the rules on the decisions of when and how much to reconfigure the machines following the workload control policy. Furthermore, it is crucial to understand how the performance of the production system is affected by the integration of the workload control with the reconfiguration of the machines for the processing time.

In response, our first research question asked: *What is the impact on the performance of controllable processing time combined with WLC method in job-shop?* Using simulation, it has been demonstrated that the reconfiguration machines to adapt the processing time can improve significantly the shop performance. Then, the workload control with controllable processing time has a positive impact on the performance measures of the manufacturing system.

In this research, it is proposed models to reconfigure all the machines or a couple of machine, and the time to reconfigure can follow a periodic or continuous review approach.

However, in response to our second research question: *what is the best combination policy continuous/periodic with proportional/dual to support the reconfiguration of processing time activities?* The results have demonstrated how the periodic-dual strategy leads to better results with adequate robustness to the bottleneck numbers and reconfiguration time.

The simulation experiments highlight how the reconfiguration of a couple of machines (dual models) is more efficient to reconfigure all machines of the manufacturing system (proportional models).

The relevant improvements regard the ability to deliver the job on time and the more uniform distribution of the workload among the machines of the manufacturing systems.

6.1 Managerial and practical Implications

The study was motivated by the use of resources with more responsiveness in the context of Industry 4.0 that improves the real-time control in manufacturing systems. The results suggest how the use of resources with controllable processing time can be introduced in the job-shop controlled with WLC and interrelated with recent smart manufacturing tools. The model proposed to support the production managers to select the better strategy considering the parameters such as the reconfiguration time and the number of bottlenecks that characterize the manufacturing system. Moreover, the manager can choose a better solution considering the costs of the reconfiguration activities composed of the fixed cost (number of interventions) and the variable costs (number of resources reconfigured).

The practical aspects concern the decision-making policy to define which machine to strengthen and which machine to weaken to improve the performance of the production system. These decisions are related to the tools, material handling and software to assigns to the machines following the proposed policies. Some practical examples in which the proposed research can be introduced are the cutting processes, multi-stage plastic deformation and assembly systems.

6.2 Limitations and Future Research

A limitation of the study is that the reconfiguration process is the same for all machines and the resources (tools and operator) that support the process area always available. Future research will evaluate the organization and management of the resources needed to the reconfiguration process.

This evaluation will be studied considering the costs to determine the trade-off between the costs and the performance improvements. Another future research concerns the training of the workers in the case of assembly systems.

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