Periodica Polytechnica Social and Management Sciences, 30(1), pp. 86–93, 2022

Workload Control and Order Dispatching Rules

Application in a Make-to-Order Manufacturing Process

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Received: 29 September 2020, Accepted: 05 January 2021,

Abstract

The purpose of this study is to choose an order dispatching rule and measure the work-in-process and lead-time in the production process of a conveyor chain manufacturer. The main strategic issue for the manufacturer is dependability, which requires meeting deadlines and managing internal lead-times. The study integrates two techniques, workload control (WLC) and an analytical hierarchy process (AHP), respectively systems for production planning and control, and multi-criteria decision support, both widely used in handling manufacturing strategic issues. The research method is a field experiment. Supported by the AHP and according to strategic criteria, practitioners selected the early due date rule (the order with the closest due date comes first) to release 231 orders. Then, employing a methodology designed to support WLC applications, the study measured key parameters that provide information regarding the overall performance of the manufacturer, the input rate, work-in-process, lead-time, throughput performance, and the level of safety stock. Using the model and a graphical tool derived from queuing theory, the throughput diagram, the study provides evidence that, although the manufacturing process is satisfactorily balanced and achieves acceptable performance, the level of safety stock is small and should be increased to prevent starvation on the shop floor.

Keywords

lead-time, inventory, safety stock, workload control, order release sequencing, decision-making aid method

1 Introduction

Manufacturing companies aim to improve their performance by employing various types of production control systems (Małachowski and Korytkowski, 2016; Reuter and Brambring, 2016; Sugiharti et al., 2019; Tamás and Koltai, 2020). Workload control (WLC) is a hybrid push-pull production planning and control (PPC) system conceived to achieve simultaneously high throughput rates and low and stable lead-times (LT). Instead of pulling jobs by means of a synchronisation device, WLC releases jobs according to the capacity of the workstations. The system admits new jobs when the work-in-process (WIP) falls below workload limits or norms. The system pushes jobs along the line, preserving the usual features of batches and queues manufacturing, which characterises a hybrid push-pull control technique (Mezzogori et al., 2019).

WLC is a control system based on order release policies developed mainly for a high variety of shopfloors with customised production schemes (Thürer et al., 2014). It has been applied mainly in job-shops (Henrich et al., 2007) but can also be found in flexible flow-shops (Sellitto and Luchese, 2018). WLC aims to keep queues stable and limited, allowing materials to flow smoothly through the manufacturing process (Costa et al., 2019). Control can extend from the initial consultation of customers to the final delivery, exploring workload hierarchies (Kingsman et al., 1989). Such integration between production and sales helps enhance the dependability of the manufacturing process (Mezzogori et al., 2019). It may also help boost other competitive factors, such as flexibility and cost reduction (Szabó, 2018).

In WLC, input and output control mechanisms balance the arrival and dispatch of orders. Input rules apply priorities to orders arriving, whereas output rules regulate production capacity. Both assure stable queues on the shop floor (Costa et al., 2019), which in turn facilitates meeting due dates (Mezzogori et al., 2019). The load-oriented orders release and addition or removal of equipment and workforce are among the most important input and output control techniques, respectively (Thürer et al., 2016a). In both, LT is the

Cite this article as: Strapazzon do Couto, B., Sellitto, M. A. (2022) "Workload Control and Order Dispatching Rules: Application in a Make-to-Order Manufacturing Process", Periodica Polytechnica Social and Management Sciences, 30(1), pp. 86–93. https://doi.org/10.3311/PPso.17271

dependent variable controlled by the amount of work-in-process (WIP): the less WIP, the shorter the waiting time in queues and therefore the lower the LT (Hutter et al., 2018) and the number of overdue jobs (Perona et al., 2016).

Protecting manufacturing from variability is a key factor for most production systems (Kundu and Staudacher, 2016). The order release mechanism ensures that jobs start just in time to meet due dates without overwhelming the system's capability (Mezzogori et al., 2019). As orders flow from a pre-shop pool to workstations, the mix, quantity, and due date of not yet released orders may change without disruptive consequences (Fernandes et al., 2020). Logical release rules avoid bottlenecks and accumulations caused by physical limitations in pools or warehouses (Liu et al., 2018). Several logical release rules exist, such as first come-first served (FCFS), earliest due date (EDD), shortest process time (SPT), and planned operation start time (PST) (Bertolini et al., 2015).

This study focuses on a manufacturer of conveyor chains for lifters whose main priority is to assure high delivery dependability. The company operates a job-shop make-to-order (MTO) plant, following a specific product design for each order. The company produces a wide variety of metal and plastic chains, modular belts, profiles, and subsidiary items, managing raw material reception from suppliers, manufacturing, delivery, installation, technical assistance, and retrofitting. The company complies with stringent technical specifications, which require advanced technologies and skilled labour.

Although simulation studies demonstrate the ability of the WLC to improve performance, reports of successful practical implementation are still limited (Liu et al., 2018). Part of the reason for this is that the theory behind the WLC relies on simulation tests using models of simple systems, which barely correspond to reality (Huang, 2017). The literature recognises the need for more empirical research on practical implementations of the WLC concept (Sagawa and Land, 2018) since they still represent a small part of the articles published in the area (Silva et al., 2015). Some previous papers such as Sellitto (2018) present theoretical models to help calculate WLC parameters in real-world applications. On the other hand, papers such as Thürer et al. (2016a) rely on simulation to evaluate LT and tardiness associated with WLC techniques.

The purpose of this study is to choose an order dispatching rule and measure the work-in-process and lead-time in the production process of a conveyor chain manufacturer. The specific objectives are to choose a logical rule to orders dispatch and measure the results of the application using a model based on WLC. The research method is a field experiment. The study's main contribution is the combination of a theoretical model with a well-known multicriteria method to help to solve a real case of a dispatching problem. To the best of our knowledge, we did not find such a combination in the recent literature.

The study addresses the input control mechanism, as recent studies have focused particularly on output controls (Land et al., 2015). Although the original focus of WLC was on highly balanced production lines, a more recent study states that the WLC could also be effective on unbalanced manufacturing plants (Sellitto, 2018), which is the current case. In such cases, particular attention should be paid to non-critical resources, since they help to protect the critical ones (Fernandes et al., 2020). The remainder of this article presents the theoretical background, methodology, results, discussion, and final remarks.

2 Background

To the best of our knowledge, the earliest published studies on WLC are Bechte (1980), Kettner and Bechte (1981), and Bertrand (1981). Wiendahl (1995) gathered early knowledge of load-oriented manufacturing control. In the WLC, the main requirement to control order waiting time and resource idleness is balancing loads among workstations (Cransberg et al., 2016). Low and stable WIP reduces variability in LT and increases dependability by increasing delivery reliability. To this end, a release choice procedure takes place in the separation pool in front of the manufacturing line. The decision-making process involves two decision levels. The first level aims, according to due dates, workloads, and estimates for processing times, to select the next order package to be scheduled. The second level, given the selected package, defines the sequence to release the embedded orders. A heuristic procedure should support the decision-making process (Thürer et al., 2014).

In the first step, the procedure defines a set of orders within a given timeframe so that the total workload, estimated by the expected number of processing hours, does not exceed the machinery capacity (Mezzogori et al., 2019). To prevent sub-optimisation, the procedure must consider the equipment in its entirety and all possible individual bottlenecks (Mezzogori et al., 2019). The remaining orders should wait in the pre-shop pool for the next launch date (Thürer et al., 2016b). The total released workload must strike a balance. It should keep queues as short as possible to prevent excessive WIP, but not too short as to risk unexpected stoppage in bottlenecks due to starvation (Chen et al., 2017). The second stage employs a dispatching method to sequence the released orders (Bertolini et al., 2015). Some usual dispatching methods (Thürer et al., 2014; Bertolini et al., 2015; Mezzogori et al., 2019) considered in this study are:

- FCFS: the arrival order is also the processing order;
- EDD: orders closest to due date come first;
- SPT: orders with lower processing time come first; and
- PST: orders with the largest criticality ([due date - current data]/estimated remaining processing time) come first.

Although the literature shows a wide range of order dispatching methods, their impact on manufacturing control is less examined (Thürer et al., 2014). This study aims to bridge this research gap by integrating the dispatching methods and a theoretical measurement model. The model aims to calculate LT, WIP, order arrival rate (RI), order delivery rate (P), and safety stocks (SS). SS is the minimum level of WIP that avoids the stoppage due to imbalances between RI and P. Order LT considers the time between arrival and completion, while part LT also considers the size of the orders. The model includes Eqs. (1) to (9) and handles isolated work centers as well as complete production lines (Sellitto, 2018):

$$\boldsymbol{LT_i} = \boldsymbol{DED_i} - \boldsymbol{ED_i}, \tag{1}$$

$$\boldsymbol{LT_m} = \sum_{i=1}^{n} \frac{\boldsymbol{LT_i}}{\boldsymbol{n}}, \tag{2}$$

$$\boldsymbol{LT_{\sigma m}} = \sqrt{\frac{\sum_{i=1}^{n}\left(\boldsymbol{LT_m} - \boldsymbol{LT_i}\right)^2}{\boldsymbol{n}-1}}, \tag{3}$$

$$\boldsymbol{LT_{mw}} = \frac{\sum_{i=1}^{n}\boldsymbol{LT_i Q_i}}{\sum_{i=1}^{n}\boldsymbol{Q_i}}, \tag{4}$$

$$\boldsymbol{LT_{\sigma w}} = \sqrt{\frac{\sum_{i=1}^{n}\left(\boldsymbol{LT_m} - \boldsymbol{LT_i}\right)^2 \boldsymbol{Q_i}}{\sum_{i=1}^{n}\boldsymbol{Q_i}}}, \tag{5}$$

$$\boldsymbol{RI_m} = \frac{\sum_{i=1}^{n}\boldsymbol{Q_i}}{\max \boldsymbol{ED_i} - \min \boldsymbol{ED_i}}, \tag{6}$$

$$\boldsymbol{WIP_m} = \boldsymbol{RI_m LT_{mw}}, \tag{7}$$

$$\boldsymbol{P_m} = \frac{\sum_{i=1}^{n}\boldsymbol{Q_i}}{\max \boldsymbol{DED_i} - \min \boldsymbol{DED_i}}, \tag{8}$$

$$\boldsymbol{SS_m} = \boldsymbol{P_m \Delta T_{max}}, \tag{9}$$

where:

- $\boldsymbol{LT_i}$ = order $_i$ lead-time;
- $\boldsymbol{DED_i}$ = order $_i$ delivery date;
- $\boldsymbol{ED_i}$ = order $_i$ entry date;
- $\boldsymbol{LT_m}$ = $\boldsymbol{LT}$ average;
- $\boldsymbol{n}$ = number of orders;
- $\boldsymbol{LT_{\sigma m}}$ = $\boldsymbol{LT}$ standard deviation;
- $\boldsymbol{LT_{mw}}$ = weighted $\boldsymbol{LT}$ average;
- $\boldsymbol{Q_i}$ = number of parts processed by order $_i$;
- $\boldsymbol{LT_{\sigma w}}$ = weighted $\boldsymbol{LT}$ standard deviation;
- $\boldsymbol{RI_m}$ = average order arrival rate;
- $\boldsymbol{WIP_m}$ = average WIP;
- $\boldsymbol{P_m}$ = average productivity;
- $\boldsymbol{\Delta T_{max}}$ = maximum time elapsed between the arrival of two successive orders; and
- $\boldsymbol{SS_m}$ = mean safety stock.

To verify graphically the analytical calculation, this study employs the throughput diagram (TD), a heuristic construction derived from queuing theory (Perona et al., 2016).

3 Methodology

This study employs a five-step research strategy. The search (July 2020 in SCOPUS and Web of Science) included peer-reviewed articles in English published in journals (not conferences) between 2014 and 2020. The keywords "Workload Control" and "Order Release" resulted in 57 articles. The keywords "Workload Control" and "Order Release" and "Dispatching Rules" resulted in only two articles. Therefore, the inclusion of dispatching rules in the study can bring some novelty to the issue.

The company's manufacturing information system provided data about 203 orders fulfilled in February 2020. The data comprise the order size, launch date, and completion date. Supported by researchers, practitioners employed the AHP to rank the dispatching methods. The group used an online tool, the AHP priority calculator (Goepel, 2018) to obtain the priority vector and the consistency ratio *CR* which is the probability that the judgment is inconsistent. How AHP calculates the priority vector is widely explained in the literature and needs not a review (see, for instance, Ishizaka and Labib, 2011). A *CR* < 10% implies a consistent judgment (Saaty, 2008).

Finally, the aforementioned model analytically calculated the overall performance of the manufacturing system. TD graphically verified the analytical results.

4 Results

4.1 Decision analysis

Five practitioners of the company employed the analytic hierarchy process (AHP) to rank the four order dispatching methods. AHP supports decisions on ambiguous alternatives when decision-makers have different opinions, as consequences are not entirely clear and may entail uncertainty. The current problem presents these characteristics. Given the non-linearity involved, it is not possible *a priori* to be sure about the most likely outcome resulting from each alternative. Simulation technique could help, but there is a certain criticism regarding its use in WLC studies since it can hardly cover all the peculiarities of a real-world manufacturing line (Mezzogori et al., 2019). Experiments with true magnitude are unfeasible, as the workload is always different. To solve the deadlock, we have chosen to use the AHP method. The method has already been employed in ambiguous situations regarding manufacturing strategic issues (Sellitto and Mancio, 2019). In the current case, experienced practitioners estimated the most likely consequences of each alternative and built a ranking to support the choice.

In a focus group session, the practitioners choose four criteria: waiting time, lead-time, order delay, and risk of sales loss. The waiting time is the time elapsed between the arrival of the order in the pool and the release to the shop floor. The lead-time is the time elapsed between the release and completion of the order. The order delay is the difference between the due date and completion. Finally, the risk of sales loss is the probability of losing sales due to insufficient promised dates caused by the dispatching method. Fig. 1 shows the structured hierarchy.

The top term is the method while criteria and alternatives are intermediate levels. Judgment uses the categories of Table 1, the fundamental scale.

Respondents answered paired questions: comparing criteria A and B, which is more important (and how different is this importance) in evaluating dispatching order rules. Table 2 shows the most selected category among the respondents and prioritises the criteria.

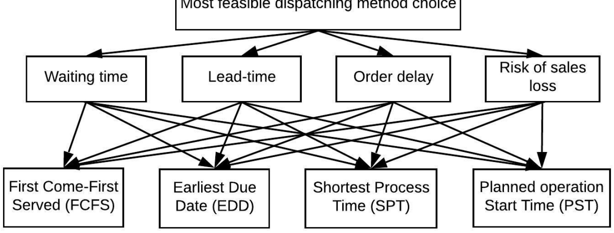

Fig. 1 Structured hierarchy for the application of the AHP

Table 1 The fundamental scale by Saaty (2008)

Definition	Weight
Absolutely equivalent	1
A small superiority	3
An intermediate superiority	5
A large superiority	7
An absolute superiority	9
Intermediate positions	2, 4, 6, 8
Inverse relationships	Reciprocals

As a criterion is equivalent to itself, the diagonal equals 1. Above and below the diagonal, judgments are reciprocal (if A is much better than B, then B is much worse than A). A similar procedure compared the order dispatching rules according to their influence on the criteria. The question was: comparing rules A and B, which is more influential (and how different is this influence) in the performance of a given criterion. Tables 3 to 6 show the results.

The respondents consider that SPT and PST rules adhere better to the waiting time criterion. They also consider that SPT adheres better to the lead-time and EDD to the order delay and risk of sales loss criteria. As the criteria have different priorities, a joint evaluation should decide on the final ranking. Table 7 shows the final ranking of dispatching rules. The results indicate the EDD rule for the field experiment.

4.2 Application: the mathematical model

A set of orders was released according to the EDD rule (closest due date first). In the first decision level, accepted orders were segregated into 28 groups. The criterion for the segregation was the due date. In a certain time lapse, the total workload of the group cannot surpass the manufacturing capacity, as stated by Thürer et al. (2014) and Mezzogori et al. (2019). In the second decision level, the pre-shop pool releases orders of the selected group to

Table 2 Comparison between criteria

CR = 4%	Waiting time	Lead-time	Order delay	Sales loss	Priority
Waiting time	1	1/3	1/3	1/5	0.076
Lead-time	3	1	1/2	1/5	0.148
Order delay	3	2	1	1/2	0.253
Sales loss	5	5	2	1	0.523

Table 3 Influence on waiting time

CR = 1%	FCFS	EDD	SPT	PST	Priority
FCFS	1	1/4	1/5	1/5	0.060
EDD	4	1	1/2	1/2	0.206
SPT	5	2	1	1	0.364
PST	5	2	1	1	0.364

Table 4 Influence on lead-time

CR = 2%	FCFS	EDD	SPT	PST	Priority
FCFS	1	1/7	1/9	1/5	0.042
EDD	7	1	1/2	2	0.284
SPT	9	2	1	4	0.516
PST	5	1/2	1/4	1	0.158

Table 5 Comparison according to "order delay" criterion

CR = 4%	FCFS	EDD	SPT	PST	Priority
FCFS	1	1/9	1/2	1/5	0.050
EDD	9	1	7	5	0.661
SPT	2	1/7	1	1/3	0.084
PST	5	1/5	3	1	0.204

Table 6 Comparison according to "risk of sales loss" criterion

CR = 4%	FCFS	EDD	SPT	PST	Priority
FCFS	1	1/9	1/6	1/4	0.045
EDD	9	1	3	4	0.555
SPT	6	1/3	1	3	0.270
PST	4	1/4	1/3	1	0.130

the shop floor, according to the EDD rule. Table 8 shows an extract of the data. The application handles the entire set of 231 orders. For parsimony, Table 8 shows only partially the entire set of orders.

The first column shows the order number assigned according to the chronological entry in the information system. For the application, the orders were sequenced according to the EDD rule, which differs from the sequence imposed by the order number. The first six columns were extracted from the information system ($\boldsymbol{DD_i}$ = due date of order $\boldsymbol{i}$; $\boldsymbol{D_i = DED_i - ED_i}$, the tardiness of order i if the order fails to meeting the due date; otherwise zero). The seventh column was calculated according to Eq. (1). The eighth column combines the sixth and seventh. Finally, the last column combines Eq. (2) with the sixth column. Table 9 summarises the results of the application.

The first eight lines result from Eqs. (2) to (9). In the last line, $\boldsymbol{D_m}$ is the average tardiness of orders = $\sum \boldsymbol{D_i/n}$.

5 Discussion

Regarding dispatching rules, the practitioners considered that FCFS presents deficiencies due to the lack of an underlying rationale. Random results hardly meet strategic needs. The PST and SPT rules may satisfy some criteria – both perform satisfactorily in terms of reducing waiting time and SPT controls LT sufficiently – but are insufficient overall. EDD is not bad in terms of any of the criteria and excels in respect of order delay and risk of sales loss. As these two aspects are the most valuable, EDD wins if multiple comparisons are made. The conclusion reinforces the perception of the practitioners that the company has deficiencies in the sales planning and customer service control.

Regarding the application, $\boldsymbol{LT_m}$ and $\boldsymbol{LT_{mq}}$ differ due to the variability in order sizes. The bivariate stochastic variable $\boldsymbol{LT_iQ_i}$ was ideated to represent the use of the manufacturing system by an order, which is directly proportional to the $\boldsymbol{LT}$ and $\boldsymbol{Q}$. A time to delivery of 3.51 days with a 95% confidence interval was calculated from the results of $\boldsymbol{LT_m}$ and $\boldsymbol{LT_{sm}}$ (0.92 and 1.32 days, respectively). Thus, accounting for four days for the $\boldsymbol{LT}$ in the promised due date is sufficient for reliable deliveries.

The average arrival rate $\boldsymbol{RI_m}$ is 21,750 sets/day and the average delivery rate $\boldsymbol{P_m}$ is 20,585 sets/day, which complies with the requirement of high throughput. As $\boldsymbol{RI_m}$ is slightly greater than $\boldsymbol{P_m}$, the manufacturing system may somehow accumulate inventory over time. Eventually, the manufacturing system should be asked to accelerate deliveries to compensate for any excess. The average inventory level $\boldsymbol{WIP_m}$ equals 31,321 sets, representing the requirement of circa 1.5 days, which is lower than the required safety stock level ($\boldsymbol{SS_m}$ = 48,992). Due to the remaining variability, the system requires more protection against starvation.

Table 7 Comparison between alternatives

	Waiting time (0.076)	Lead-time (0.148)	Order delay (0.253)	Sales loss (0.523)	Ranking
FCFS	0.060	0.042	0.050	0.045	0.047
EDD	0.206	0.284	0.661	0.555	0.515
SPT	0.364	0.516	0.084	0.27	0.266
PST	0.364	0.158	0.204	0.13	0.171

Table 8 Raw data and the EDD model application

#	ED_i	DED_i	DD_i	D_i	Q_i	LT_i	LT_iQ_i	$(LT_m - LT_i)$
5	01/02 00:00	03/02 09:54	01/02 00:50	2.38	102	2.41	246.13	2.23
1	01/02 00:00	01/02 03:11	01/02 02:08	0.04	268	0.13	35.59	0.62
4	01/02 00:00	03/02 23:19	01/02 09:25	2.58	1178	2.97	3500.91	4.21
6	01/02 00:00	03/02 16:43	01/02 23:07	1.73	2492	2.70	6719.89	3.16
7	01/02 00:00	06/02 17:03	02/02 00:17	4.70	2352	5.71	13431.25	22.95
...	...	...	...	...	...	...	...	...
199	24/02 00:00	24/02 17:18	25/02 21:58	0.00	604	0.72	435.38	0.04
195	24/02 00:00	24/02 09:52	25/02 22:25	0.00	2444	0.41	1006.17	0.26
198	24/02 00:00	25/02 20:52	26/02 00:12	0.00	1015	1.87	1897.93	0.90
192	24/02 00:00	24/02 15:48	26/02 01:49	0.00	2096	0.66	1380.69	0.07
201	24/02 00:00	24/02 01:52	26/02 02:05	0.00	320	0.08	24.95	0.71
...	...	...	...	...	...	...	...	...
230	27/02 00:00	27/02 07:26	29/02 01:47	0.00	1940	0.31	601.29	0.37
223	27/02 00:00	27/02 22:12	29/02 03:06	0.00	4752	0.93	4397.03	0.00
226	27/02 00:00	27/02 19:20	29/02 04:46	0.00	2656	0.81	2140.66	0.01
214	27/02 00:00	28/02 18:51	29/02 04:46	0.00	9580	1.79	17108.39	0.75
231	28/02 00:00	28/02 03:00	29/02 04:47	0.00	512	0.13	64.03	0.63

Table 9 Application results

Variable	Result	Unit	Equation
$LT_m =$	0.92	days	2
$LT_{\sigma m} =$	1.32	days	3
$LT_{mw} =$	1.44	days	4
$LT_{\sigma w} =$	1.80	days	5
$RI_m =$	21,750	sets/days	6
$WIP_m =$	31,321	sets	7
$P_m =$	20,585	sets/days	8
$SS_m =$	48,992	sets	9
$D_m =$	0.41	days	–

Finally, Fig. 2 uses the TD diagram to depict the results graphically (in the figure, the acronym acc means accumulated variables).

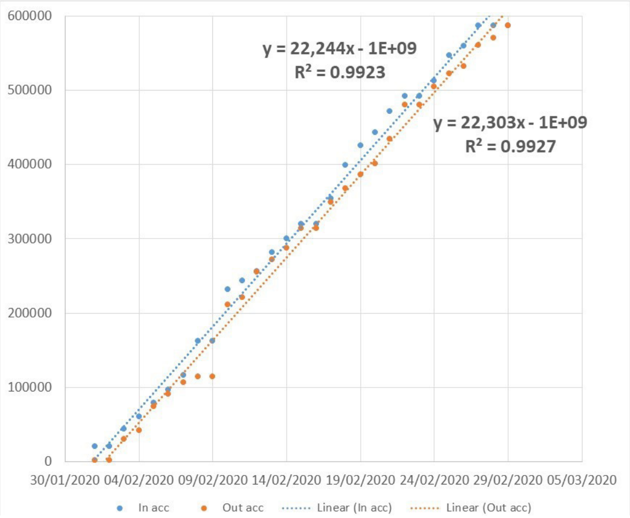

Fig. 2 TD and regression model

In the TD, the regression models satisfactorily represent the real data since both R^2 are close to one. The input regression curve allows verifying the calculation of $\boldsymbol{RI_m}$, whereas the output regression verifies $\boldsymbol{P_m}$. Both slopes (22,244 and 22,303) are close to the calculated values, reinforcing the validity of the model. Again, eventual differences are due to the remaining variability. The diagram helps to verify the low level of safety stock ($\boldsymbol{SS_m}$). On more than one occasion, both curves touch themselves, which means starvation (all the material already entered in the shop floor has already exit and nothing is in the process now). To reach $\boldsymbol{SS_m}$, management should accelerate the release of new orders, eventually combining with a momentary decrease in the processing capacity, sufficient to balance the shop floor.

6 Final remarks

The article presented a combined theoretical and empirical study in a job-shop MTO manufacturing that produces chains and conveyors to lifters. The study integrated two techniques, WLC and AHP. An order dispatching rule (EDD) was chosen and applied to a set of 231 orders performed in a lapse of time of one month. The results of the application were provided by a mathematical model, verified by a graphical tool. The main conclusion is that the EDD rule provided delivery dependability and achieved an acceptable balance between inputs and outputs of the shop floor. Nonetheless, a low level of average safety stock resulted, which may induce management to accelerate releases or even slightly reduce the capacity to prevent starvation.

The proposed decision support structure represents a simple and practical tool that can be used in future WLC implementations. Data availability and empirical evidence are essential to improve the practical applicability of WLC and correlated techniques. However, the existence of unreliable suppliers, seasonal production, and low-consumption items should still be considered when establishing new inventory levels. It should be noted that the WLC represents an effective way to implement lean principles in the context of customised production. The main underlying idea of WLC is to limit the amount of workload admitted on the manufacturing shop floor. This limitation reduces waiting time in queues in the manufacturing systems, which also reduces the total flow time. Consequently, inventory control allows controlling also orders lead-time.

Further studies should encompass replication to different kinds of manufacturing processes, such as flow-shops and make-to-order. Further studies should also consider different industries, such as the electric and electronic, footwear industries, and miscellaneous materials that operate with order release rules. Finally, further research should also focus on improving the method, simultaneously studying the influence of order uncertainty and inventory, and including other techniques, such as the fuzzy set theory to manage the intrinsic uncertainty in inventory management.

Acknowledgment

The authors would like to thank CAPES and CNPq, the Brazilian research agencies, for supporting this research (grants numbers 88887.492901/2020-00 and 302570/2019-5).

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