From Machine Utilisation to Flow Time: Effects of Lean Transformation on Scheduling

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Abstract

The Lean paradigm transforms a production company from utilisation-centric planning into a system in which other operating conditions such as short flow times, local control, and reduction in variation are weighted as well. This paper studies how the scheduling of production changes when the above three conditions are implemented. Their effects are studied by constructing an optimisation model for the scheduling of a flow shop. The optimisation model is based on the following ideas. First, when the flow time is emphasised, the objective of the scheduling changes from utilisation to a short flow time. Second, if local control is used, it means that the optimisation is done locally, i.e. individually at each station, and it concerns the makespan at the station. Third, if the variation is reduced, the processing times and arrival times have less variation and the scheduling can force the flow times to have less variation by using first-in-first-out (FIFO) sequencing. The experimental results achieved using the model describe how and in which order the operating conditions under study should be implemented in the scheduling. For example, if utilisation is important, local control and FIFO should not be used before variation is reduced.

1. Introduction

When companies undergo Lean transformation, they start to use different techniques, such as SMED, Kanban, Kaizen, and Heijunka, to streamline their production. Different Lean techniques affect production through different mechanisms. These mechanisms can be grouped on the basis of the type of effect they have on the operating principle of the system and operating conditions. Some methods focus on reducing flow time, some increase the flexibility of the production, e.g. by using local control, and some permanently reduce disturbances and thus variation.

In the literature, it is often emphasised that all the Lean techniques should be used if Lean is applied, or otherwise production does not improve significantly. Focusing on just a single technique is often seen as the main problem in Lean implementation (see e.g. [1, p. 10]). However, it might be that some techniques are more relevant than others because of the way they change operating conditions and consequently different measures of performance. For example, the Toyota production system, on which Lean is based, has two pillars, which are autonomation (i.e. smart automation) and just-in-time [2, p. 77]. As described in [1, p. 32], these pillars stand on stability, which is the foundation for all the other methods. In other words, this means that variation should be reduced first, and after that the processes should be automated and the material flow balanced. Following these ideas, this paper tries to find out how important different operating conditions are when the scheduling of a flow shop is considered. The emphasis is put on finding out what kind of changes to operating conditions are required and in which order they should be implemented when a Lean transformation occurs.

Lean itself is a buzzword that combines multiple ideas that aim to reduce waste in production. As stated by Liker [1, p. 20], many ideas come from the pioneering work done by Ford [3] and Ohno [4]. Lean has been studied quite extensively during the last few decades (see e.g. [5]). However, as recently reviewed by Powell et al [6], studies describing a sequential process for Lean implementation, which is in focus in this paper, are few. One such study, by Åhlström [7], concludes, based on a case study done at a Sweden-based company, that management should put simultaneous effort into all aspects of production, first the quality issues and then, after the quality issues are resolved, managers should shift to the continuous improvement initiatives. This is related to the original pillar idea described in

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the above paragraph. In general, Lean techniques improve flow times by making WIP low, but on the other they improve the utilisation of the system by reducing variation and increasing capacity. This complexity makes it hard to study Lean methods together quantitatively, and thus they are often studied one at a time. For example, in a review done by Kumar and Panneerselvam [8] studies dealing with Kanban-based methods are common.

This paper presents a quantitative optimisation model to study the potential effects of Lean transformation on scheduling a flow shop. Scheduling itself is broadly studied in the literature. The reader who is unfamiliar with scheduling and optimisation may study e.g. the books by Conway et al. [9] and Pinedo [10]. In short, the scheduling arranges jobs for the different resources, with the objective being to balance between the utilisation of the machines and the flow time of the jobs. The scheduling problem becomes complex when the system consists of multiple machines. This is also a case in which Lean transformation often seems to be effective. A special case of multiple machines, a flow shop, is studied in this paper. In a flow shop, the jobs are always processed on the machines in the same order. This kind of production process is common in manufacturing industry. Scheduling of the flow shop has been considered earlier from the Lean perspective (see e.g. [11], [12] and [13]), but according to our knowledge, performance of scheduling in different phases of Lean transformation has not been studied earlier.

The paper is organised as follows. Section 2 first discusses how the three operating conditions studied, i.e. flow time, local control, and variation reduction, relate to Lean techniques, and second, describes an optimisation model constructed to study the effect of these operating conditions on flow shop scheduling. In Section 3, the model is used in numerical experiments to study how the weights on the operating conditions affect the performance of the scheduling. The results are discussed in Section 4, and they suggest that if the utilisation is important, flow time can start to be reduced immediately, local control only when the process is somewhat stable, and FIFO control only if the processing times of the process are stable. Finally, Section 5 presents final conclusions.

2. THE LEAN OPERATING CONDITIONS IN SCHEDULING

2.1. LEAN TECHNIQUES AND OPERATING CONDITIONS

Our paper studies three types of operating conditions that lie behind the use of Lean techniques. These are short flow times, local control, and variation reduction. When a Lean transformation takes place, these three operating conditions are realized at the planning level. Next, we point out how these operating conditions are achieved using different Lean techniques. A more complete analysis of Lean techniques, or actually the techniques in its predecessor philosophy JIT (just-in-time), is done by Bartezzaghi and Turco [14].

The first operating condition to be studied, *Short flow time,* is achieved in Lean by limiting work-in-process (WIP), reducing batch sizes, and increasing capacity. First, limiting WIP reduces flow time in production. In production where utilisation is high, it is almost impossible for an increase in WIP to increase throughput without increasing the flow time. Thus the opposite is also true. If the utilisation is high, a decrease in WIP will reduce the flow time. An example of a Lean technique that reduces WIP is Kanban, a control system based on cards that start the production and are released from the downstream of the production. It reduces WIP by limiting the number of parts in process to the number of the cards. A second way of reducing flow time is reducing lot sizes. For a single machine, if there is a batch of N items and setup time S and processing time t, the flow time is $N * t + S$. One-piece flow could reduce the flow time in this case. However, it increases the need for setups, which have to be shortened in order to be efficient. This is achieved in Lean by using the SMED (single minute exchange of dies) technique. A third way to reduce the flow time is to have extra capacity or more flexible capacity. This reduces the flow time, simply because the capacity is available.

The second operating condition that is studied, *Local control,* allows simplified decentralised production control. This is not a very new idea as locally applied solutions are often used in practice. The problem with local control is that it might impair the overall control of the production. This is often seen in a functionally working company, where the utilisation of single machines is important, but the whole picture is not so clear. However, the production controllers usually push global targets, and thus may find local control secondary from their point of view. Kanban and 5S are examples of Lean methods that are typically implemented just locally. 5S reduces different types of waste on the factory floor.

The third operating condition that is studied, *Variation reduction,* is achieved by e.g. reducing disturbances permanently, increasing capacity, and reducing batch sizes. Disturbances are usually reduced in Lean by using the 5S method. According to Hopp et al. [15, p. 264], batches increase variation in future stages of production. It is common that companies using Lean techniques also use FIFO sequencing. A reason for this might be that FIFO is a simple priority rule that gives a relatively low flow time variation (see e.g. [9, pp. 188-189] and [16, pp. 227]).

It should be noted that flow time, local control, and variation reduction are also closely connected and the relations between the conditions are not very clear. For example, after variation reduction, it is easier to shorten the flow time by reducing WIP. Local control makes it easier to react to changes, which reduces variation and flow time as well. However, as a result of the limited local view, it might be that some variations are caused by the local control. Figure 1 illustrates the relationships between the conditions.

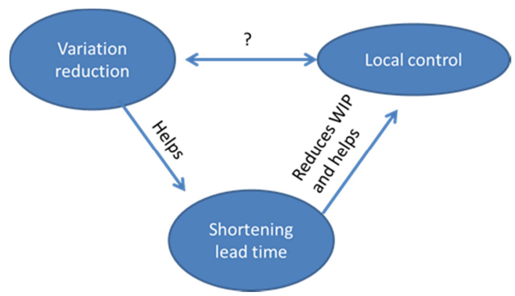


Figure 1. Relationships between the operating conditions that are studied.

2.2. *FLOW SHOP SCHEDULING MODEL*

To study the effects of the three types of operating conditions described above, an optimisation model for flow shop scheduling is constructed in this section. The basis of the model is the normal flow shop scheduling problem. It is considered as an offline problem where the processing times of the jobs for all the machines are known. The basic model is extended so that the different operating conditions caused by the Lean transformation are handled as follows. First, shorter flow times can be achieved by changing the objective from the traditional makespan towards flow time. Second, if local control is used, the previous objectives can be calculated machine-wise and their sum is minimised. Third, variation reduction is modelled in two ways: processing times can be generated using processing times with smaller variation and scheduling can reduce the flow-time variation using the FIFO processing order. The used notation for parameters and decision variables is the following.

Parameters:

M – Number of machines

J – Number of jobs

p_{mj} – Processing time of job j on machine m (variation in processing times describes the status of Lean transformation)

w_{flow} – Flow time weight (describes the status of Lean transformation)

w_{local} – Local control weight (describes the status of Lean transformation)

w_{fifo} – FIFO control weight (describes the status of Lean transformation)

Decision variables:

t_{mj} – Starting time of job j on machine m

l_m – Makespan on single machine

l – Makespan of the whole schedule

$t_{\max,m}$ – Maximum finish time of jobs on machine m

$t_{\min,m}$ –Minimum starting time of jobs on machine m

f_j – Flow time of job j

f – Total flow time

In the normal flow shop scheduling problem, there are *J* jobs processed on *M* machines in the same sequence. *j* denotes a single job and *m* a single machine so that $j \in [1,2,..,J]$ and $m \in [1,2,..,M]$. Each job *j* has processing time p_{ij} on each machine *m*. The scheduling of the flow shop has the following constraints.

$$t_{mj_k} \geq t_{mj_l} + p_{mj_l} || t_{mj_k} + p_{mj_k} \leq t_{mj_l}, \quad \forall m \in [1,2,..,M], j_k \in [1,2,..,J], j_l \in [1,2,..,J], j_k \neq j_l \tag{1}$$

$$t_{(m+1)j} \geq t_{mj} + p_{mj}, \forall m \in [1,2,\ldots,M-1], j \in [1,2,..,J] \tag{2}$$

$$t_{mj} \geq 0, \forall m \in [1,2,\ldots,M], j \in [1,2,..,J] \tag{3}$$

Equations (1) prevent two jobs from being processed at the same time on a machine. Equations (2) define the order of the jobs on the machines, i.e. jobs have to be processed first on the first machine and after that on the second, and so on. Equations (3) define the earliest starting time for processing.

The scheduling result of the system changes, depending on the objectives. In this paper, the objectives 1) makespan, 2) local makespan, and 3) flow time are studied.

The *makespan* is the total length of the schedule. It also indirectly represents the utilisation of the system. It is denoted by *l*. If it is minimised, it can be calculated for the flow shop using the following equations.

$$l \geq t_{\max,M} - t_{\min,1} \tag{4}$$

$$t_{\max,M} \geq t_{Mj} + p_{Mj}, \forall j \in [1,2,\ldots,J] \tag{5}$$

$$t_{\min,1} \leq t_{1j}, \forall j \in [1,2,\ldots,J] \tag{6}$$

The makespan as an objective can also be used locally. The *local makespan* is the makespan for a single machine. If the sum of the local makespans is minimised, the local makespan for a machine *m* is calculated as follows.

$$l_m \geq t_{\max,m} - t_{\min,m}, \forall m \in [1,2,\ldots,M] \tag{7}$$

$$t_{\max,m} \geq t_{mj} + p_{mj}, \forall m \in [1,2,\ldots,M], j \in [1,2,\ldots,J] \tag{8}$$

$$t_{\min,m} \leq t_{mj}, \forall j \in [1,2,\ldots,J] \tag{9}$$

The *flow time* is the total flow time. The single flow time for an individual job *j* is denoted by f_j. The total flow time is denoted by f. It can be calculated as follows.

$$f_j = t_{Mj} + p_{Mj} - t_{1j}, \forall j \in [1,2,..,J] \tag{10}$$

$$f = \sum_{j=1}^{J} f_j \tag{11}$$

In contrast to the makespan, the local flow time is omitted because it would give similar results to the total flow time. If there were e.g. a transfer time between machines, the local flow time could be different.

The above objectives are combined in the objective function

$$minimize\ (1 - w_{flow}) * ((1 - w_{local}) * l + (w_{local}) * \sum_{m=1}^{M} l_m) + w_{flow} f, \tag{12}$$

where w_{flow} and w_{local} denote the weights allotted to flow time and local control. Both of these weights can be varied from 0 to 1. If w_{flow} is zero, the makespan is the main objective, and if it is one, the flow time is the main objective. The local weight, w_{local}, complicates this. It can be used to make the sum of the makespans of individual machines the objective instead of the makespan. If w_{local} is zero, the makespan is the objective and if it is one, the sum of the makespans of individual machines is the objective. The actual values for the weights are defined by the current status of Lean transformation.

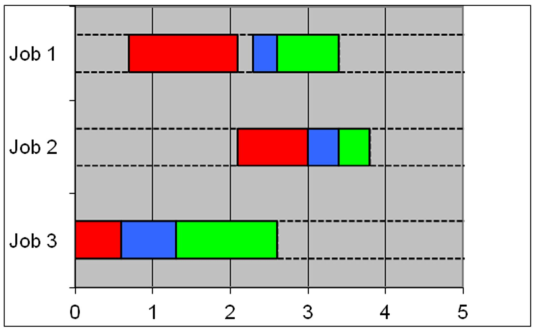
FIFO is an additional constraint. It forces the jobs to be processed in the order they arrive. The third weight, FIFO weight, w_{fifo}, forces production to follow the FIFO order in the production if set to one; otherwise, it is zero and the order is determined freely by other factors. The current status of Lean transformation define if the FIFO weight is zero or one. If FIFO control is used, it is implemented by replacing the equations (1) with the following:

$$t_{mj} + p_{mj} \leq t_{m(j+1)}, \forall m \in [1,2,\ldots,M], j \in [1,2,..,J-1] \tag{13}$$

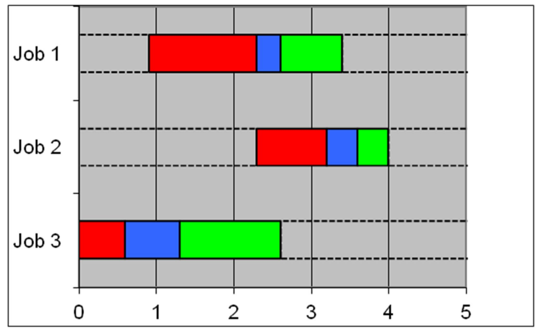
3. Numerical Experiments

Using the optimisation model described above in Section 2, the effects of Lean operating conditions are studied in the numerical experiments of this section. First, example schedules are presented for a 3-machine 3-job flow shop and then more general numerical experiments are performed for a 3-machine 5-job flow shop. In the experiments, the optimisation models were solved optimally using IBM ILOG CPLEX Optimization studio V12.6.

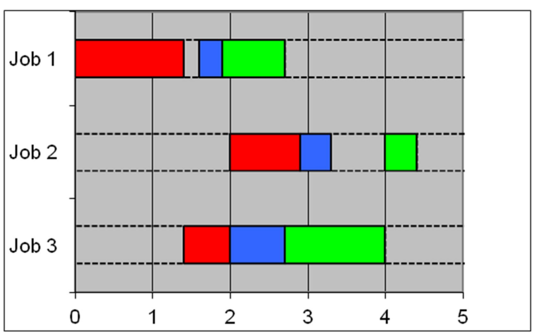
Figure 2 illustrates schedules achieved with different weights generated using the model for a 3-machine 3-job flow shop. The processing times of the 3 jobs in the example are: (1.4 0.3, 0.8), (0.9, 0.4, 0.4), and (0.6, 0.7, 1.3). The figure shows how the schedule is affected when the objective is either (a) makespan, (b) flow time, (c) local control, or (d) FIFO order. All of the cases yield a different makespan and total flow time. Note that the purpose of the example is to represent the differences between the different objective weightings, not their general performance.



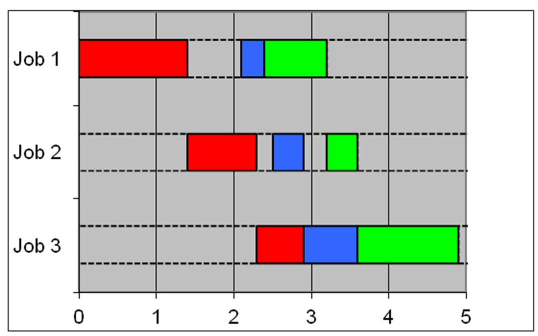
a) Makespan as objective.
w_{flow}= 0, w_{local} = 0, w_{fifo}=0,
l (makespan) =3.8, f(total flow time) =7.0.



b) Total flow time as objective.
w_{flow}= 0.9, w_{local} = 0, w_{fifo}=0,
l (makespan) =4.0, f(total flow time) =6.8.



c) Local control and makespan as objective.
w_{flow}= 0, w_{local} = 0.5, w_{fifo}= 0,
l (makespan) = 4.4, f(total flow time) = 7.7.

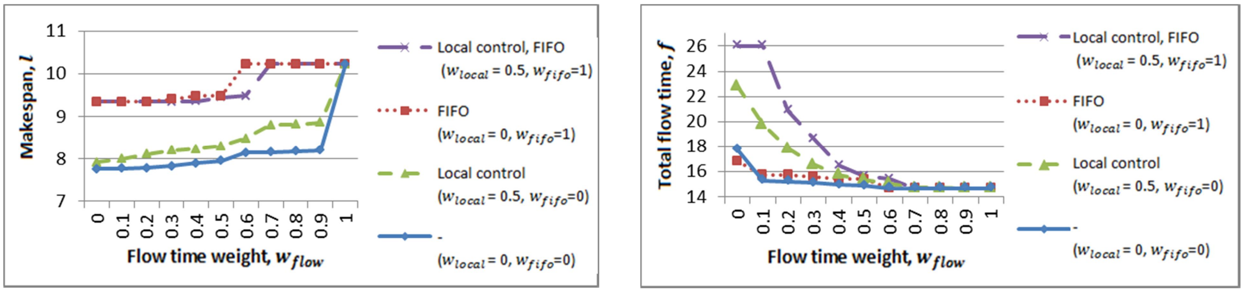


d) FIFO and makespan as objective
w_{flow}= 0, w_{local} = 0, w_{fifo}= 1,
l (makespan) = 4.9, f(total flow time) = 8.

Figure 2. 3-job 3-machine flow shop schedules with different objectives. Different colours represent different machines.

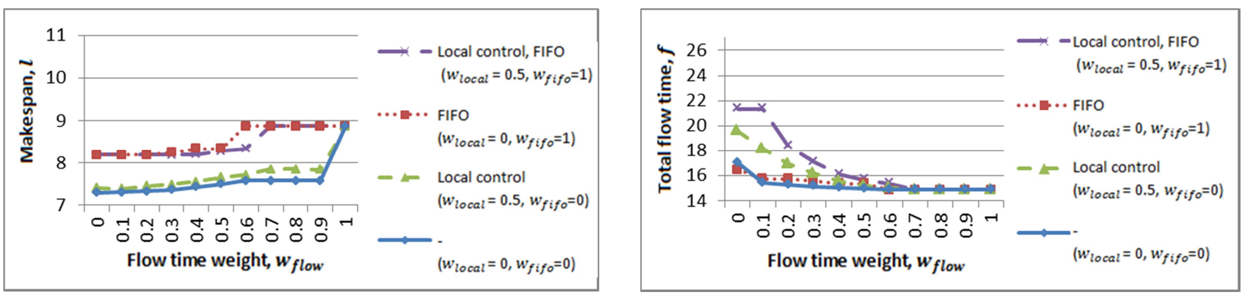
Next, the effects of the different conditions are studied more generally in the case of a 3-machine 5-job flow shop. Two experiments are performed in which two different processing time distributions are used. In the experiments, the parameters are the flow time weight, w_{flow}, local control weight, w_{local} , and FIFO weight, w_{fifo}. The flow time weight, w_{flow}, is varied from 0 to 1 in steps of 0.1. The local control weight, w_{local} , is either 0.5 or 0. The FIFO weight, w_{fifo}, is either one or zero. In both experiments, 50 different scenarios are generated and solved for each parameter value combination.

The first processing distribution is the exponential distribution with lambda = 1. This means that the processing time *CV* (coefficient of variation) is also 1. For this case, Figure 3 shows how the flow time weight, local control weight, and FIFO weight affect the makespan and flow time. The second distribution is Erlang distribution with λ = 4, K = 4. This means that the processing time *CV* is 0.5, and thus the variation is smaller than with the exponential distribution. For this case, Figure 4 shows how the flow time weight, local control weight, and FIFO use affect the makespan and flow time.



a) Average makespan b) Average total flow time

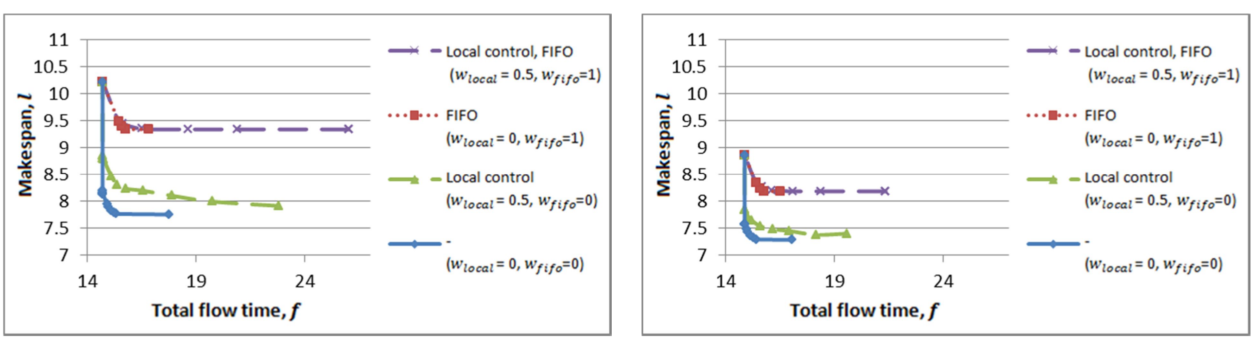
Figure 3. The impact of the flow time weight, local control, and FIFO on the makespan and flow time with exponential distributed processing times (CV = 1.0).



a) Average makespan b) Average total flow time

Figure 4. The impact of the flow time weight, local control, and FIFO on the makespan and flow time with Erlang distributed processing times ($\lambda = 4$, $K = 4$, $CV = 0.5$).

Finally, Figure 5 compares the two cases by showing the previous results in flow time-makespan charts. The best schedules are the ones that have both a low makespan and a low total flow time, the ones that are near the bottom left-hand corner in the charts.



a) Exponentially distributed processing times (CV = 1) b) Erlang K = 4, lambda = 4 distributed processing times (CV = 0.5)

Figure 5. Makespan-flow time charts with different flow time weights.

4. Results and Discussions

This section analyses the experimental results that were described in Section 3. The purpose is to find out the order in which the operating conditions that were studied should be implemented when a company starts a Lean transformation from a utilisation-centric production to a Lean company.

First, the results from the example in Figure 1 show that different objectives can result in totally different schedules. This makes the problem interesting as this means that the matter of how the operating conditions should be implemented is not trivial. Makespan clearly minimises the makespan and lead time clearly minimises the lead time. Local control makes the local makespan of the second machine shorter, which makes the total makespan worse. In the case of FIFO, the processing order is restricted and thus the results become worse.

The results with high process time variation are shown in Figure 3. The result shows that in this case, both FIFO and local control make the makespan worse, as expected. On the other hand, weighting the flow time even by 0.9 does not increase the makespan significantly. All this suggests that the flow time can start to be reduced first, whereas local control and FIFO cannot be used if there is high variation in process times and the makespan is still important.

However, if the process time variation is moderate or can be reduced, which is the case in the results shown in Figure 4, the situation changes. It is interesting to notice that local control might be a reasonable choice here. By looking at the results in Figure 5 the same can be seen again. The schedules with local control appear to give flow times that are similar to the schedules achieved without local control.

It should be noted that the results are limited numerical case studies, and thus they can only be used to reject a possible general hypothesis. In this case, this means that FIFO and local control should not always be used in the case of high process time variation and FIFO cannot always be used in the case of moderate process time variation.

However, to sum up, the results suggest the following sequence for the implementation of the different Lean operating conditions: flow time, variation reduction, local control, and finally FIFO order. If utilisation is important, local control and FIFO should not be used with high variation. Local control, however, might still be used if there is moderate variation. The use of FIFO clearly requires a stable process if utilisation is important.

5. Conclusions

The paper studies what kinds of changes to operating conditions are required and in which order they should be implemented when a Lean transformation takes place. First, the paper points out that three types of operating conditions, short flow time, local control, and variation reduction, are important underlying factors in the use of Lean methods. Second, these factors are used in an optimisation model in order to study them in the scheduling of a flow shop. In the model, the above three operating conditions are realised by weighting the lead time, using local objectives, and using FIFO ordering with different processing time variations. The model is used in experimental analysis to study the effects of operating conditions. The main results from the experiments are the following.

- in different operating conditions totally different schedules can be obtained in the case of a 3-machine flow shop;
- in the case of high processing time variation, flow times can start to be reduced without significantly affecting utilisation;
- local control and FIFO should not be used in the case of high processing time variation if utilisation is important;
- if moderate variation is achieved, local control can be used together with flow time without making utilisation low;
- FIFO control should only be used if the variation is low or utilisation is not important.

The results in the paper are experimental and thus the findings should be extended in future research. Using heuristics, more complex cases with higher numbers of machines could be studied. Continuous case models where orders arrive indefinitely would also be an interesting area of extension.

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