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Workload control under diagnosis

Soepenberg, Gerrit Dinant

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Chapter 5.

Adapting workload control for complex job shops

5.1. Introduction

A job shop can be typified as a production situation in which a large number of different products are manufactured according to customer specification. Job shop production situations are often associated with routing sequence variability, but they can diverge considerably in terms of routing lengths and interrelationships between orders. Job shop literature often focus of manufacturing independent (single-level) orders with routing steps varying between 1 and 6 operation steps (Melnyk and Ragatz, 1989; Thürer et al., 2010b). However, some job shops are confronted with interrelated suborders, which require assembly (multi-level orders), and with considerably longer routings. These kinds of situations can be positioned on the left side of the job shop production applicability area (visualized in Figure 5.1). In terms of product complexity characteristics the orders manufactured in these job shops are comparable to (small) projects. However, in contrast to project processes, many orders are executed in parallel. As such, this environment is referred to as a complex job shop in the remainder of this paper.

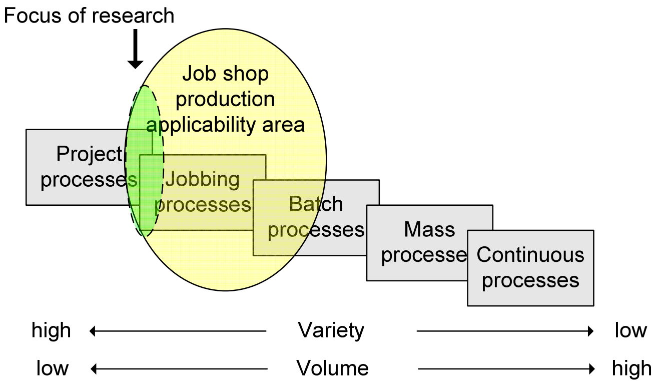


Figure 5.1. Distinction in process types based on variety/volume characteristics. (Adapted from Hayes and Wheelwright (1979) and Hill (1989)).

Achieving high logistical performance in a job shop is a difficult task, as the *variability* regarding orders often causes control problems. The consequences of this variability are especially prevalent with long routings and assembly structures. Even when processing times and routings are known beforehand, predicting the future state of an order is nearly impossible. Only a small disruption of an order at a station can have severe consequences for the progress of the order itself and for many other orders. Even more robust methods like the workload control (WLC) concept, known as the leading PPC concept for manufacturing situations dealing with high variability and uncertainty (Stevenson and Silva, 2008), do not provide adequate answers for long and assembly type routings (see, for example, Henrich et al. (2004)). As such, a need exists for a control concept that can effectively control delivery performance in complex job shops.

The main aim of this paper is to adapt the WLC concept for complex job shops, by means of combining insights from existing concepts with insights from a real life job shop, experiencing long and assembly type routings. The paper starts by reviewing literature on how PPC concepts deal with complex job shops. Next, it is discussed how a studied real-life job shop, which does not use WLC, deals with long and assembly type routings. For this purpose a detailed analysis on the progress of orders in the company for a three months period is presented. This analysis creates an understanding how the delivery performance is achieved in this practical situation and which problems the company faces. The last part of the paper derives guidelines that are incorporated in an adapted WLC control concept for job shops with long and assembly type routings, combining insights from literature and the case company.

5.2. Literature Review

Controlling the progress of orders in complex job shops can be regarded as a real challenge: resource constraints for many operations far ahead as well as the interrelations between orders, when assembly type routings are present, should be considered. Theoretically, multi-project planning approaches are capable of dealing with both issues (see, for example, Herroelen and Leus (2004) and Hans et al. (2007)). However, the uncertainty originating from the large amount of complex orders that have to be produced parallel to each other and that share resources makes multi-project planning approaches generally not manageable here. As such, we focus the remainder of the literature review on job shop control approaches.

A widely used approach for job shop control is deterministic scheduling (see for a review Jain and Meeran (1999)), which is known to perform relatively well for small and less complex job shops. However, besides considerable computer calculation times, one of the main disadvantages of this detailed deterministic approach is that it neglects variability in terms of unpredictable changes often encountered in job shop type production. When routings are long and contain assemblies, variability often results in deviations between predicted and actual behaviour. As a consequence regenerating the schedule is frequently required in practice and certainly not desirable for complex job shops.

Another approach that is widely studied is the use of priority dispatching rules, traditionally considered the only decision variable under the control of shop floor personnel (Melnyk et al., 1994). In several studies (Fry et al., 1989; Reeja and Rajendran, 2000; Choi and You, 2006; Natarajan et al., 2007) dispatching rules have been evaluated for controlling order progress in job shops with relatively complex order flows. Although a general understanding when a given dispatching rule works well is lacking (Hopp and Spearman, 2001), valuable insights can be retrieved from these studies. Generally, the findings from these studies indicate that due date based rules perform relatively well with assembly type routings. These rules can help to synchronize the progress of suborders and thus avoid long assembly waiting times. On the other hand throughput time reducing rules as shortest processing time (SPT) are less effective because speeding up on suborder to be assembled, may just increase its waiting time at assembly. Despite their acknowledged merits, dispatching rules are regarded as a relatively weak mechanism if they are used alone (Hendry et al., 1998). Therefore, other options for control have been developed.

In that respect many researchers started to acknowledge the contribution of restrictive order release to the shop floor as a powerful instrument for control. It resulted in the development of the Workload Control (WLC) concept, nowadays regarded as the most suitable PPC concept for job shop production (Stevenson et al., 2005). WLC aims to control throughput times on the shop floor by incorporating restricted release of customer orders to the shop floor, while maintaining an order pool prior to release, which buffers against the many uncertainties involved with job shops. This concept aims to prioritize orders before release and often uses simple flow conserving rules as first-in-first-out (FIFO) (Bechte, 1994). Direct benefits of controlled release relate to improving throughput by means of balancing workloads (Land, 2004), avoiding earlier completion of products (Lu et al., 2010) and increasing flexibility in terms of being able to respond to late order cancellations or changes (Melnyk and Ragatz, 1989).

Although the benefits of controlled release are widely acknowledged, also the ability of WLC to cope with long and assembly type routings is regarded limited. First, orders with long routings have difficulties being released, as they have to comply with many workload norms (Perona and Portioli, 1998). Furthermore, it is difficult to control the future order flow already at the release moment (Henrich et al., 2004). Release decisions regarding orders are based on the status on the shop floor at the time of release. This status can have changed considerably at the time orders arrive at their downstream operations. This uncertainty is even increased in assembly type situations. As such, the high amount of uncertainty questions the main idea of limiting the potential of order progress control on the shop floor itself. The study of Lu et al. (2010) in assembly type job shops shows that the influence of priority dispatching should not be neglected with controlled release, and that interaction effects between release approaches and dispatching rules can be observed. Bertrand and van de Wakker (2002) show that releasing interrelated suborders separately at their planned release dates is risky and leads to poor performance. Based on a simulation study they propose to release all interrelated suborders at the same time and use ‘speed’ differences between suborders with different routing lengths. This contradicts the common idea in WLC to create a constant and predictable flow rate in the shop.

Concluding, the WLC concept can be regarded as an effective solution for job shop control. However, uncertainty caused by long and assembly type routings will require additional order progress control after release of orders to the shop floor. The next section provides insights into a potential direction for improvement by means of an empirical analysis. It analyses a real life complex job shop, which manages to deliver many orders right in time.

5.3. Empirical research project

This section discusses the results of an empirical analysis in a company that can be characterized as a complex job shop. The first part of the section provides a concise introduction to the company and its current PPC. The second part presents the quantitative analysis on delivery performance determinants for a three months period. The main focus is on exploring how the company manages orders to be delivered right on time and on assessing the influence of complexity characteristics on order progress.

5.3.1. Case description

The case company manufactures precision tools and dies for the production of small electronic devices. It can be typified as a make-to-order company. The company is the result of a split-up of a large company. Although many products are still delivered to this large company, the company also started to deliver to other original equipment manufacturers (OEMs). As this split-up and delivery to new customers has required a shift from an internal focus to an external focus, delivery performance is being regarded increasingly important in this company.

Products

Several product categories can be distinguished in the company: dies, stamps, electrodes and ultra precision systems. Also measurement activities are executed based on external requests. Besides the production of new products to customer order, repair activities of broken (machine) parts are performed or these parts are replaced. As such, a wide variety of products are manufactured.

Resources

The company possesses approximately 40 workcentres, which each perform a specific operation. As the diverse set of products require a wide range of different operations, the shop floor is organized in a functional layout. Operating the workcentres requires specialized skills, which results in limited interchangeability of employees between workcentres.

Order characteristics

Within the composition of a complete customer order, two types of underlying work orders can be distinguished (see Figure 5.2). Each customer order consists of a production order which includes the final operations. The second type is a suborder. Suborders represent parts required to manufacture the final production orders. The manufacturing of these suborders is needed for 21% of all production orders. When suborders are required, operations of the final production order typically consist of several assembly operations and/or collection and inspection operations before being sent to the customer. Overall, relatively long and assembly type routings are observed in the company. Table 5.1 provides some descriptive statistics regarding the orders. The upper part of the table presents the characteristics of the full order, including the production order and possible suborders. The middle and lower part contain the specific characteristics of the production orders and suborders respectively.

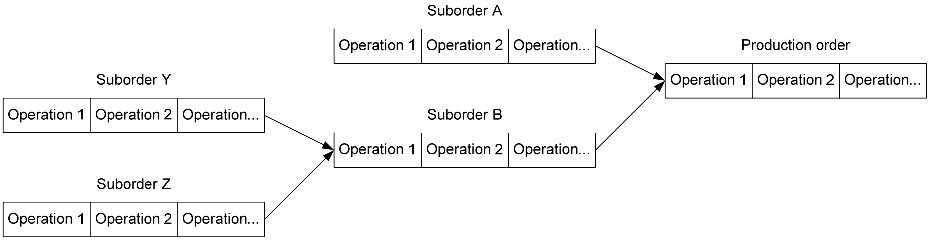


Figure 5.2. Order structure in company.

Table 5.1. Descriptive statistics regarding orders.

Characteristics of the full order structure	Total number of orders		1082
	Number of operations	Average	11
		Standard deviation	20
		Range	1-344
	Processing hours per operation	Average	9
Production order characteristics	Total number of production orders		1082
	Number of operations	Average	5
		Standard deviation	3
		Range	1-18
Suborder characteristics	Percentage of production orders with underlying suborders		21%
	Number of suborders per production order	Average	6
		Standard deviation	7
		Range	1-56
	Number of operations	Average	4
		Standard deviation	3
		Range	1-24

Production planning and control

The order acceptance/realisation process normally starts with determining delivery dates. Delivery dates are often negotiated between account managers or planners and the customer. For this purpose a rough cut capacity planning overview is available, consisting of the total amount of processing times of accepted orders for each workcentre. However, in practice most delivery dates of products are fixed and long delivery times are often not accepted by the customer. As an alternative some of the operations can be outsourced when bottlenecks are detected.

The order process continues with process planning, after which the required materials are ordered. When materials arrive, orders are immediately available for production on the shop floor. As such, no restrictive release of orders to the shop floor is performed. To deal with the considerable amount of orders on the shop floor, the company employs four highly skilled planners, mainly responsible for their own product category. However, coordination is required, as product categories can make use of the same resources.

The planners are supported by means of a system using backward scheduling based on finite capacity. This system schedules the orders according to their planned processing times backwards from their delivery dates. The main performance criterion for the scheduling system is to maximize the number of orders delivered on time. It should be noticed that no buffer times are included in the calculations, which causes many changes even by tiny disturbances. Each night a new schedule is created, based on the current situation on the shop floor. The main task of the planner is to track the progress of the individual orders in the system. When problems arise they often expedite 'priority orders' on the shop floor and make the necessary adjustments in the scheduling system. Finally, when orders are finished, they are shipped to the customer.

5.3.2. Empirical analysis

Performance measures

This section provides an analysis of the delivery performance of the company. To gain insights into the delivery performance of the company, order progress on the shop floor is analyzed in detail for a three months period. The focus of the analysis is on how order progress at each operation contributes to the final lateness of an order. In that sense order progress at each operation is analyzed in terms of whether urgent orders are accelerated and less urgent orders delayed. To create a reference which orders are urgent at a certain stage, the estimated lateness is calculated. As in (Soepenberg et al., 2008), estimated positive or negative lateness of a production order at the arrival of a certain operation means that the corresponding order would be delivered tardy or early respectively, when the operation throughput times in its remaining routing would all be equal to the average throughput times for those operations (see equation 1). In our ex-post analysis the average operation throughput times are based on all of the 1082 investigated orders which required that operation.

$$L_i = \sum_{j \in S_i} \overline{T}_j \; - \; (D - t_i) \qquad (1)$$

With L_i = estimated lateness of the order upon arrival at operation i, S_i = the set of operations still to be performed starting with i, $\overline{T}_j$ = Average throughput time required for operation j, D = due date of the order, t_i = time of arrival at operation i.

Order progress diagrams, developed in earlier research (Soepenberg et al., 2008), can be helpful to visualize the order progress of individual orders by showing the changes in estimated lateness of individual orders after each stage. Here we use a more aggregate view by depicting the estimated lateness distributions across all orders at several points in the order flow. To structure the analysis, we first divide orders progress on the shop floor into two main stages. Order progress at each stage is analyzed separately (see Figure 5.3). The first stage is the manufacturing of the suborders, defined as the time between the release of the first suborder until the completion of the last suborder. The second stage is the manufacturing of the final production order, defined as the time between the availability of the final production order until completion of the final production order. The availability of the final production order is defined as the completion of the last suborder. When no underlying suborders are required, the release time of the production order determines its availability on the shop floor. In addition to order progress characteristics, we investigate the influence of complexity characteristics related to each stage, such as routing lengths (1 and 2) and number of suborders (3).

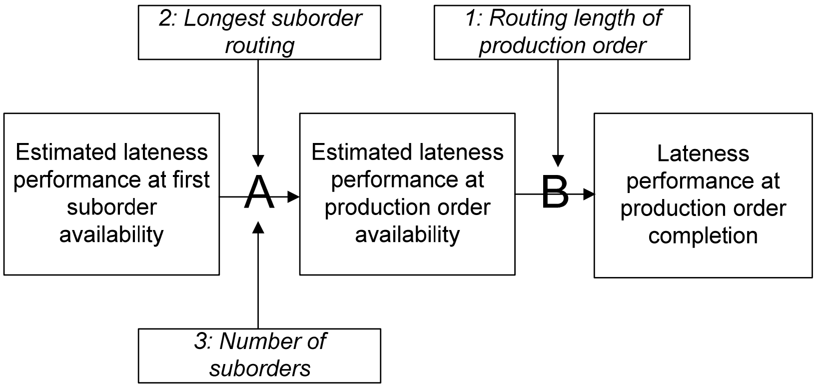


Figure 5.3. Research model.

The next subsection starts our analysis at the final stage before delivery, the manufacturing of the final production order (stage B).

Analysis part 1: The progress of production orders on the shop floor

The estimated lateness at the time of production order availability is shown in the left histogram in Figure 5.4. Comparing this distribution with the final lateness distribution at production order completion (right histogram) indicates that the variability of lateness at production order availability is considerably higher. More than 50% of the orders are estimated to be delivered tardy at production order availability, i.e. more than 50% would be tardy if their remaining operation throughput time would be average. Contrarily, the final percentage tardy at production order completion is 22%. This suggests that prioritizing during the manufacturing of the production order enables to reduce this variance considerably.

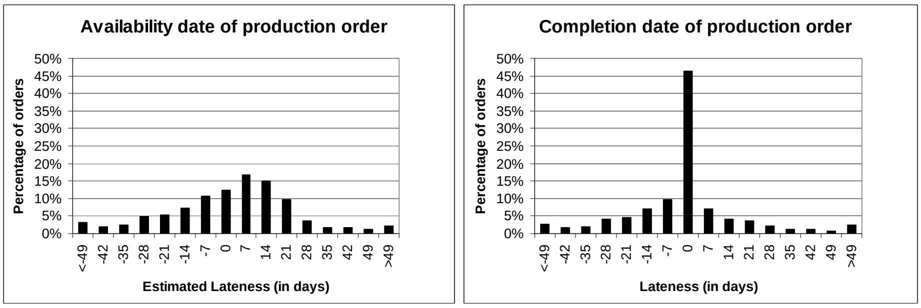
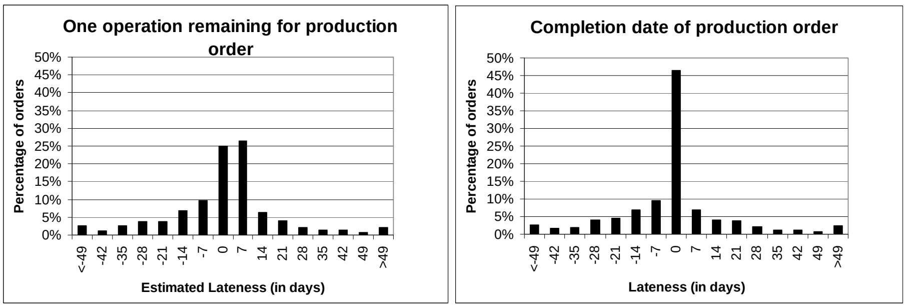


Figure 5.4. Estimated lateness at production order availability vs. lateness at production order completion.

Further analysis is performed to locate more precisely where prioritizing takes place during the manufacturing of the production order. This analysis reveals that especially during the last operation of the production order the percentage of orders to be delivered tardy is reduced considerably, i.e., from 45% to 22%.

Figure 5.5 shows the relevant histograms. In contrast to the left histogram in Figure 5.4, which shows the estimated lateness distribution at production order availability, the left histogram in Figure 5.5 shows the estimated lateness distribution as calculated just one operation before production order completion. Even here the distribution still shows a large dispersion of estimated lateness across orders.


One operation remaining for production order

Completion date of production order

Figure 5.5. Estimated lateness at one operation remaining for a production order.

It is interesting to know whether this phenomenon of accelerating at the final stages of manufacturing as observed in Figure 5.4 and Figure 5.5 also holds for production orders with high routings lengths. For this purpose we carried out more detailed analysis on production orders with routing lengths of 7 and more operations. Each bar in Figure 5.6 reflects the estimated lateness distribution for a certain number of operations still remaining. Colors represent the level of estimated lateness at the time of arrival at the operation. In the legend the upper limit of the class is specified, i.e. the class of 7 contains the percentage of order that is estimated tardy, but no more than 7 days. We can see that when 7 operations are still remaining, more than 50% of the orders is still estimated to be more than 7 days late. According to this figure the company manages to decrease the estimated lateness of the lengthy production orders step-by-step from 6 operations on. However, the final on time delivery of many production orders is mainly achieved by a considerable acceleration during the last operation step, which corresponds to our earlier findings based on Figure 5.5.

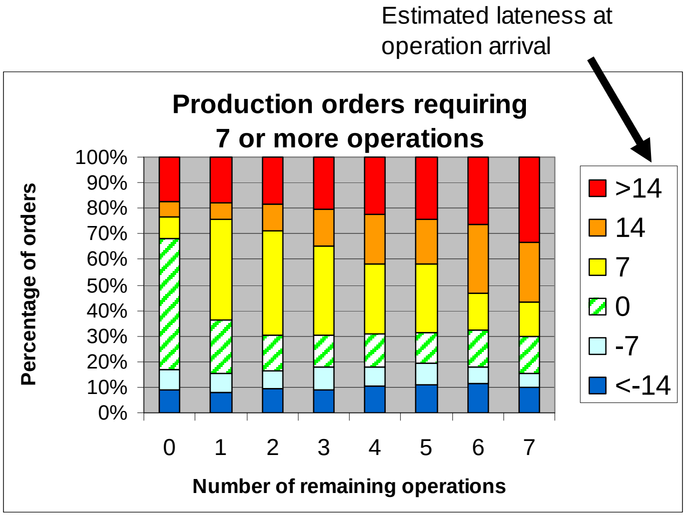

Estimated lateness at operation arrival

Figure 5.6. Change in estimated lateness after each remaining amount of operations.

Analysis part 2: The progress of suborders on the shop floor.

Part of the production orders require several suborders to be completed before the manufacturing of the (final) production order can start. Table 5.2 provides some descriptive statistics which show that delivery performance of these production orders is relatively poor compared to overall performance.

Table 5.2. Descriptive statistics regarding delivery performance and shop floor throughput times

Delivery performance statistics	Production orders without suborders	Percentage delivered tardy	18%
		Average lateness	-5 days
		Standard deviation of lateness	22 days
	Production orders with suborders	Percentage delivered tardy	38%
		Average lateness	0 days
		Standard deviation of lateness	42 days
Shop floor throughput time statistics	Production orders without suborders	Average	31 days
		Standard deviation	30 days
	Production orders with suborders	Average	67 days
		Standard deviation	39 days

To gain insights into the determinants of the relatively poor performance of production orders incorporating underlying suborders, order progress of both order types is plotted separately in Figure 5.7. The figures on top and bottom of the figure show the distribution of estimated lateness of production orders with underlying suborders and production orders without underlying suborders respectively. Comparing figures B-C and D-E clearly show that priority setting during manufacturing in the production order stage reduces the dispersion of estimated lateness considerably for both order types. However, the situation at production order availability is worse for production orders with underlying suborders (B), as the distribution lies more to the right compared to production orders without underlying suborders (D). It is probably the result of factors affecting performance before production started (for example, delivery date promising), as the estimated lateness distribution of suborder availability (A) already shows a considerable dispersion. Additionally, it can be hypothesized that the complexity of production orders regarding suborders could influence its progress on the shop floor. This is analyzed with the help of Figure 5.8.

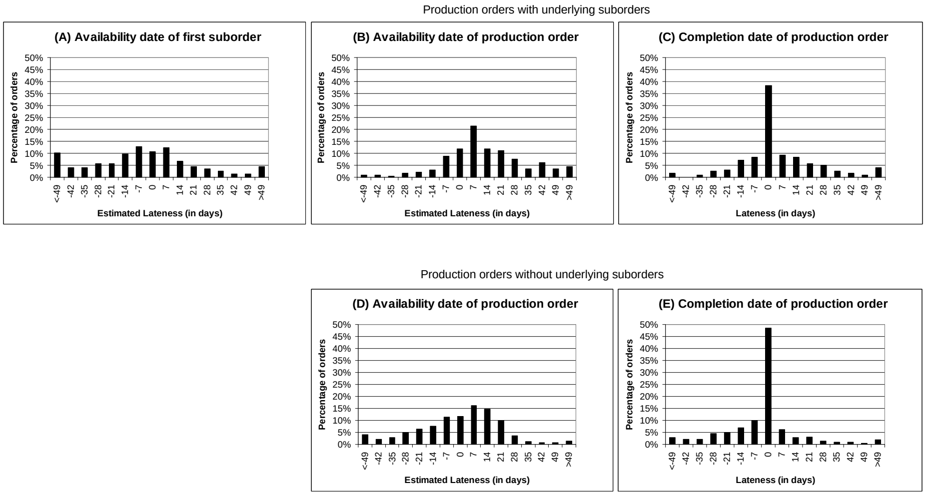


Figure 5.7. Estimated lateness distributions at several points in the order flow for production orders with and without underlying suborders.

The three histograms on top of Figure 5.8 show the relationship between the number of suborders and the estimated lateness during the progress of orders. The three histograms on the bottom show the relationship between the routing length of the longest suborder of a production order and order progress on the shop floor. Each bar in Figure 5.8 reflects the estimated lateness distribution for orders with a certain number of suborders or suborder routing length. Colours represent the level of estimated lateness. For example the first bar in the upper left diagram shows that from all orders requiring just one suborder approximately 60% are estimated to be delivered on time or early at the availability date of the first suborder. It should be noticed that the number of suborders and maximum routing length are related, as the probability of observing a long routing will be higher when more suborders are required for a production order. Both figures show that no general relationship exists between the complexity characteristics and performance. Only in case suborders require a very long routing (>8 operations), the percentage of production orders with a positive lateness value of more than 14 days at the time of production order availability increases considerably. Further analysis reveals that most of the orders in this category are also finally delivered tardy, despite accelerations during the manufacturing of the production order. Thus, the results indicate that only when suborder complexity of orders exceeds a certain threshold value, the company is not able to control their progress sufficiently.

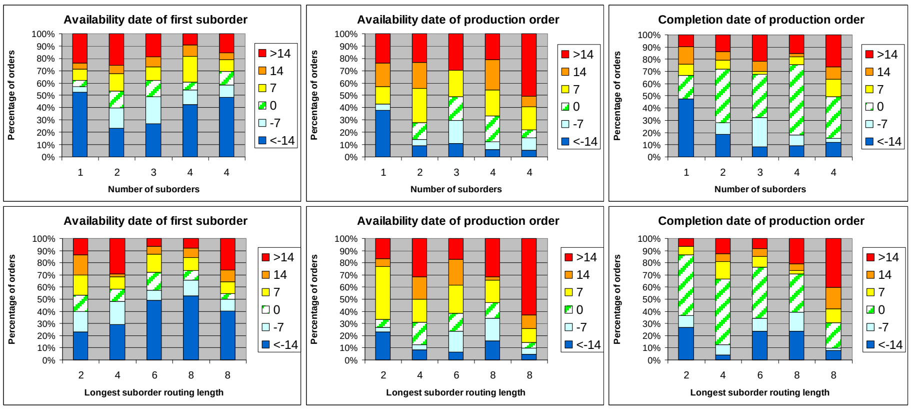


Figure 5.8. The effect of the number of required suborders (upper row of graphs) and the maximum routing length of suborders (lower row) on order progress.

The performance analysis in this section has shown that on time delivery in the case company is mainly achieved during the manufacturing of the production orders. Many production orders that are estimated to be delivered tardy at its availability date are finally delivered on time. A more in-depth analysis shows that on time delivery is often realized by means of a considerable acceleration in the very last production step, even for orders with long routings. An analysis of suborder complexity reveals limited influences on performance. Only when suborder routing lengths exceed a certain threshold value, the estimated lateness before the production order can start gets relatively high. In these cases accelerations during the manufacturing of the final production orders cannot prevent these orders from being delivered tardy.

5.4. Adapted WLC approach to deal with long and assembly type routings

This section presents an adapted WLC concept in order to deal with job shops confronted with long and assembly type routings. The concept is developed based on insights from literature and the empirical study.

The WLC concept as presented in literature tries to control order progress on the shop floor mainly by means of focused release of orders to the shop floor. It considers both the workload situation for the workcentres in the order routing and the relative urgency of orders to be released. However, with long and assembly type order routings, the release decision has to take place long before the order will affect the direct workload of the workcentres. Seen from another perspective, the long routings also allow for more emphasis on progress control at later stages of the order routing. The case company shows for example that releasing orders immediately and fully controlling the progress of orders on the shop floor can result in reasonable performance. However, also the company approach has its limits as some delays, especially for complex orders, in an early progress stage appear to be irresolvable at later stages on the shop floor. In an adapted WLC concept we intend to make use of the potential of correcting order progress disturbances on the shop floor, but using the advantages of controlled release to restrict order delays in the beginning of a routing.

Adaptations to deal with long routings

Our approach is to adapt the WLC concept in order to reflect the actual prioritizing of orders performed by planners in practice more realistically. As a guideline for priority setting, operation due dates (ODDs) are used. Normally, ODDs can reflect the urgency of an order at each workcentre in any stage of the order progress. Within WLC, ODDs reflect the idea of realizing constant workloads and operation throughput times. As such, ODDs within a context of WLC will be derived from the due date, by backward scheduling with predetermined planned operation throughput time. However, when a planner in practice can choose between two orders approaching their ODD, one order at the beginning of its routing and one at its end, the latter will normally be chosen. Delaying the order at the end will certainly lead to late delivery, while delaying an order early in its routing can still be corrected for later on. Of course, the latter possibility is even more prevalent when routings are longer. In order to enable this prioritization at the end, our approach is to plan longer operation lead times for an order early in its routing. Although it may seem a minor change, it has several consequences for the WLC concept. The resulting pattern of planned operation lead times and ODDs is visualized in Figure 5.9.

Notice that besides the longer operation lead times at the beginning of a routing, another buffer is inserted at the end of the routing in order to cope with any remaining fluctuations inherent to a practical situation. However, for the buffer time to have effect, it should be stressed that order progress at the last step should still focus on completion at the internal ODD.

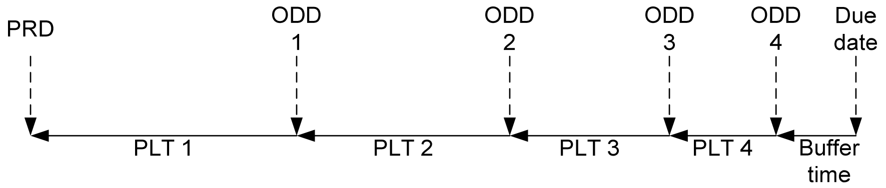


Figure 5.9. Influence of varying planned operation lead times (PLT) per operation (ODD = operation due date, PRD = planned release date).

The proposed adaptations have consequences for the release procedure. In general it will provide orders with different planned release dates (PRDs), which are also supposed to be more realistic. However, there can be several reasons to actually deviate from these PRDs. For example it is reasonable for a planner to give priority to an order with only few operations, when it comes to making choices between orders which tend to exceed their planned release date. In addition workload norms many not allow for releasing orders on their PRD. It is well known that particularly orders with long routings or large processing times have more difficulty being released, because they have to comply with many workload norms (Perona and Portioli, 1998; Thürer et al., 2010b). When using ODDs this might lead to severe progress corrections at the first workcentres, as for example, the first ODD may have been passed already. Literature already pointed out that using ODD may interact negatively with a WLC release method (Land, 2004). A well considered order selection at release can thus be cancelled out as soon as the order is on the shop floor. Therefore, we propose that ODDs should be recalculated at the actual release moment, i.e. the remaining slack should be redistributed across operations.

Thirdly, the load calculation procedure at release should take the longer planned operation lead times at the beginning of a routing into account. Several types of workload accounting methods have been proposed in literature. All methods aiming at a high variety of routings use certain accounting principles which are often based on the assumption of constant flow rates of orders (Land, 2004). This assumption is clearly violated by our adaptations. However, the method of corrected aggregate load calculating, which is regarded as the most robust method for practical situations (Thürer et al., 2010a), can be adapted to our proposed progress pattern. In its basic form this method corrects the load contribution of a released order for the position of an operation in the routing of the order. The basic calculation mostly used in literature determines the load contribution of an order to the i^th^ workcentre in its routing as the operation processing time (p_i) divided by the position number (i) of the operation in the routing. However, this simple correction is based on the assumption of equal operation throughput times (Oosterman et al., 2000). In case of strong differences, it suggests a ratio of planned operation throughput times which should be used as a correction factor. More precisely the contribution to the load of the workcentre performing the ith operation should be calculated when an order is released as $\frac{PLT_i}{\sum_{j=1..i} PLT_j} \; p_i$, with PLT_i being the operation lead time planned for the ith operation. Also in this factor planned operation lead times should be recalculated, based on the actual release date, similar to the suggestion in the previous paragraph.

WLC adaptations to deal with assembly type structures

The proposed use of ODD will also facilitate the coordination required for assembly operations. The literature review already showed that priority rules may play a significant role in this coordination. More specifically interrelatedness of orders results in additional waiting times when assembly operations have to wait for completion of all underlying suborders. As such, planned operation lead times and planned release dates should incorporate these assembly waiting times, in order to reflect order progress on the shop floor more realistically. When assembly waiting time would not be planned, the ODD of the first assembly operation would be too tight and leads to strong corrections of order progress compared to the planned pattern. The example in Figure 5.10 visualizes this assembly waiting time for a production order that needs two underlying suborders to be finished before assembly can start. Both suborders require two operations each. When suborders require different amounts of operations, also Bertrand and van de Wakker's

(2002) suggestion to synchronize the progress of the underlying suborders by means of using different flow rates for orders with different routing lengths can be applied. This would imply a combination of different flow rates in different stages of order progress as suggested in this paper and a differentiation in flow rates among suborders.

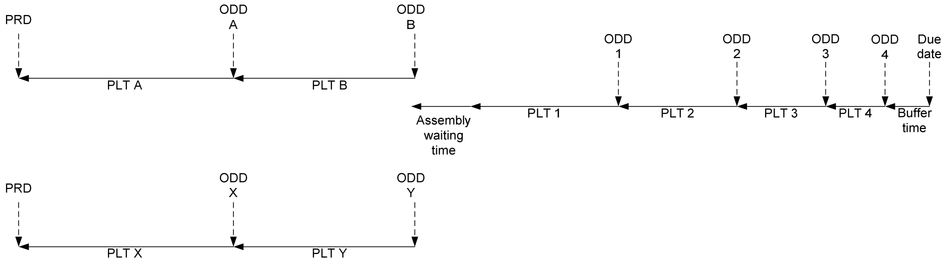


Figure 5.10. Incorporating assembly waiting times.

Concluding, the adaptations proposed to deal with long and assembly type routings should make the WLC concept more suitable, as the possibilities for progress control on the shop floor are incorporated. The changes require a more sophisticated WLC approach, as the adjustments require planned operations times per operation to be dependent on the positioning of operation in its routing. However, WLC now reflects more realistically the actual prioritizing used on the shop floor. As such, it is likely that the adaptations will contribute to effective practical implementations of the concept in complex job shops.

5.5. Conclusions

Starting point for this paper is the need to develop a PPC concept that can deal with job shops with long and assembly type routings. The literature review reveals that, despite the fact that WLC is seen as the most appropriate PPC concept for job shop production, its main focus on release does not suffice for these complex job shops. Restricting the workload in a job shop limits the effectiveness of priority dispatching for order progress control. At the same time, particularly when orders have long routings, the importance of order progress control on the shop floor cannot be neglected. Furthermore, the WLC concept does not incorporate a mechanism to synchronize order progress of interrelated suborders in assembly type structures.

To derive potential directions for improvement, a detailed empirical analysis of order progress in a complex job shop is performed. The empirical results reveal that order progress control at the last stages of manufacturing can be used effectively. Accelerations at theses stages resulted in many orders to be delivered on time. However, the company also showed a need for a means to avoid irresolvable delays at earlier order stages.

The WLC concept may particularly help in controlling the early stages. Based on the empirical findings, adaptations to the WLC concept are proposed. The adaptations should enable exploiting the possibilities for progress control in later order progress stages. As opposed to the regular aim of WLC to create predictable and constant flow rates, we suggest the use of more realistic longer planned buffer times for early routing steps, to allow the prioritizing of other orders close to their due dates. Enabling prioritizing of orders at the end of their routings is shown to have several implications for the WLC concept. The paper discusses required changes, which relate to planned lead times, the use of priority rules both on the shop floor and at release, and the load calculation procedure at release. To improve the interaction between the WLC release method and priority dispatching on the shop floor, shop floor priorities should be recalculated after the actual release moment has been determined. Furthermore, to deal with the inherent difficulty of synchronization, it is proposed to explicitly incorporate buffer times in the planned operation lead times of assembly operations. The changes aim to result in a WLC concept that is better capable of dealing with the needs of order progress control in complex job shops.

This study proposes a novel concept based on WLC inspired by findings from an empirical study. Future research could verify and refine the proposed adaptations in for instance simulation studies.