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Workload control under diagnosis

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Chapter 2.

The order progress diagram: a supportive tool for diagnosing delivery reliability performance in make-to-order companies

2.1. Introduction

High delivery reliability is one of the order winning performance criteria for make-to-order (MTO) companies. For controlling and improving delivery reliability a good diagnosis is necessary. A first requirement for a good diagnosis is having good performance indicators. Much literature is written on guidelines to set up performance indicators for delivery reliability, see, for example, NEVEM (1989), White (1996) and Neely et al. (1997). However, performance indicators can only signal the level of performance. Support is required for revealing the causes of a bad performance in the so-called diagnosis phase (Stoop and Bertrand, 1997). This paper focuses on developing supportive tools for the diagnosis phase.

It is important for the diagnosis phase that the supportive tool links performance indicators to those decisions that can affect the performance. In this paper we confine ourselves to decisions related to production planning and control (PPC). We make use of the PPC decisions distinguished by the WLC concept, a PPC concept that is especially suited for MTO companies (Kingsman and Hendry, 2002). As such a distinction is made between PPC decisions related to input control (order acceptance/delivery date promising, order release and priority dispatching) and decisions on output control (adjusting capacities). Insights from WLC also help in determining which performance indicators should be linked with these input and output control decisions. It shows how achieving high delivery reliability is a combination of controlling average throughput times and controlling the progress of individual orders (Land, 2004). Speeding up average throughput times reduces the average lateness; keeping individual jobs on schedule reduces the variance of lateness across jobs (Baker, 1974).

In this paper the average lateness and the variance of lateness are regarded as the performance indicators that cover the two main dimensions of delivery reliability. A supportive tool that clearly indicates how input and output control decisions affect the control of the average lateness is the throughput diagram and this has been well-described in literature (for example, Bechte, 1988; Wiendahl, 1995). As will be shown the throughput diagram gives limited support for diagnosing the variance of lateness. Tools adequately relating the variance of lateness to the progress of individual orders and to the decisions affecting this progress are lacking in literature. This paper fills the gap by presenting a tool especially developed for diagnosis related to the variance of lateness. This tool is called the order progress diagram. It helps to determine the origin of order progress disturbances and uneven flow patterns and - similar to the throughput diagram – it provides the link with input and output control decisions.

The paper is organized as follows. Section 2 elaborates on the input and output control decisions, as distinguished in the WLC concept, and shows their influence on the average lateness and the variance of lateness. An available tool for facilitating diagnosis related to the average lateness, the throughput diagram, is discussed in section 3. In section 4 the new tool focusing on support of diagnosis related to the variance of lateness is presented. In both sections 3 and 4 the use of the tools is illustrated by industrial data. Section 5 concludes the paper.

2.2. The influence of PPC decisions on delivery reliability

This section discusses PPC decisions and their influence on delivery reliability performance. PPC decisions for MTO companies can best be divided into input and output control decisions (Kingsman, 2000). The framework of the WLC concept, as introduced by Land and Gaalman (1996), gives a good overview of relevant input and output control decisions (see Figure 2.1).

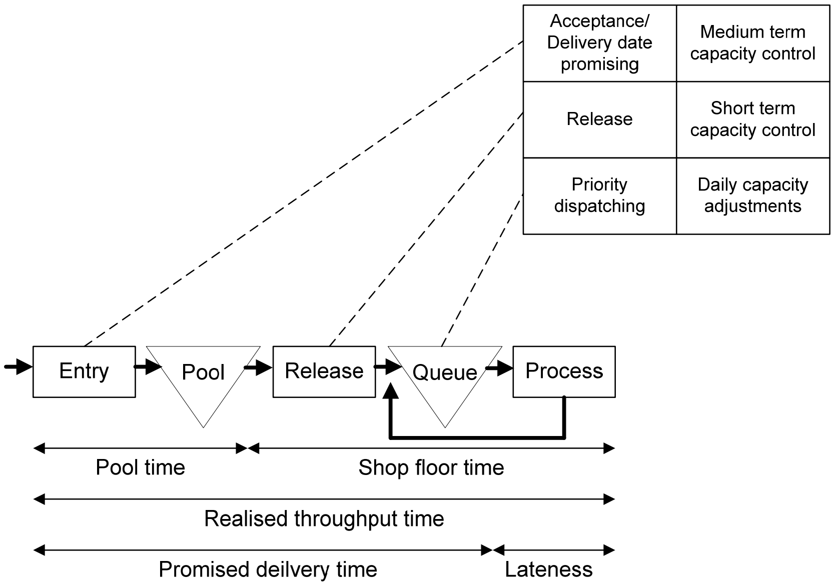

Figure 2.1. Input and output control decisions.

Input and output control decisions can influence both the average lateness and the variance of lateness. Lateness is defined as the conformity of a schedule to a given due date (Baker, 1974). It is measured by subtracting the promised delivery time from the realised throughput time. We can distinguish positive lateness (orders are delivered late) and negative lateness (orders are delivered early). The role of respectively reducing the average and the variance of lateness can best be illustrated by Figure 2.2. Figure 2.2 represents a distribution function of lateness. The vertical line indicates zero lateness. Orders right to this line are delivered late and the shaded area represents the percentage of orders delivered late. The percentage of orders delivered late can be decreased by reducing the average lateness (Figure 2.2b), and/or by reducing the variance of lateness (Figure 2.2c).

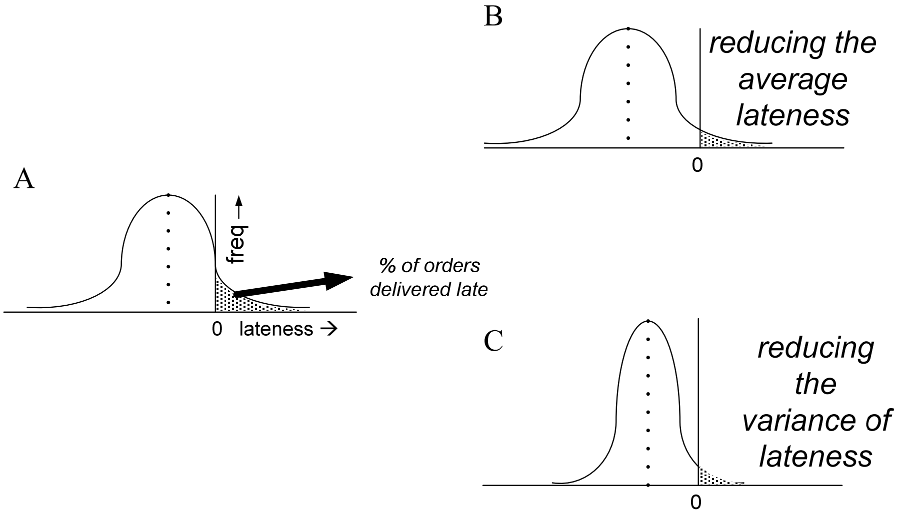

Figure 2.2. The influence of the average lateness and the variance of lateness.

For each PPC decision in Figure 2.1 the influence on the average lateness and the variance of lateness can be specified.

The first input control decision distinguished is order acceptance and delivery date promising. This control decision deals with customer enquiries. Customer enquiries can arise in a variety of ways. Sometimes customers completely determine the delivery dates of orders; in other situations the company has a strong influence on the promised delivery dates (Park et al., 1999). Dealing with customer enquiries entails a complex process of decision making and we refer to Kingsman et al. (1996) for an extensive discussion on relevant acceptance and due date promising decisions for MTO companies. The process will result in a number of orders to be produced in a certain period with a promised delivery date for each order. Notice that the average lateness is the difference between the average realised throughput time and the average promised delivery time. The average lateness will increase when a larger number of orders have to be produced in a certain period assuming both capacity and promised delivery dates remain the same. So increased congestion and waiting times will result in a longer average realised throughput time. The average lateness will also increase if tighter delivery dates are promised for the same set of orders, because in this situation the average promised delivery time component decreases. The variance of lateness is more specifically influenced by the characteristics of the accepted orders. For instance orders with a larger number of operations to be performed will generally require larger throughput times. If throughput times of individual orders are insufficiently taken into account when due dates are promised, the variance of lateness will also likely increase.

The next input control decision is the release of orders. Because capacity is often restrictive, it is important to select those orders for release that provide capacity groups in the shop with a good load balance. This will support the control of the average lateness (Land, 2004). Balance of loads results in smooth flows on the shop floor and avoids congestion in front of certain capacity groups. The release decision can also contribute to a low variance of lateness. This is achieved by considering relative urgency of orders in selecting the orders to be released next. In order to be able to accurately determine this urgency, reliable throughput times are required. The control of these throughput times is another function of the release decision.

The last input control decision considered here is priority dispatching. Priority dispatching is a relatively weak input control decision (Kingsman and Hendry, 2002). Once an accurate release decision has been made, priority dispatching has a limited influence on the average lateness and the variance of lateness. However, some dispatching rules exist that still improve the average lateness, for example SPT and WINQ, and some that reduce the variance of lateness, like EDD and ODD (Land, 2004).

Finally, output control decisions can dedicate capacity to those capacity groups where orders are congesting. Capacity changes are generally triggered by large sets of orders, tending to be delivered late. Therefore output control decisions usually focus on controlling the average lateness of orders. By chasing specific requirement peaks across time, the variance of lateness may be reduced as well.

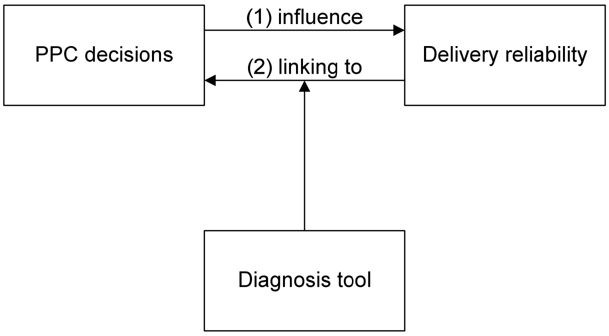

Figure 2.3. Diagnosis framework.

This section has concentrated on the influence of PPC decisions on delivery reliability performance (arrow (1) in Figure 2.3). A good diagnosis of delivery reliability performance requires that the measured performance can be traced back to these PPC decisions, as shown by arrow (2) in Figure 2.3. A well-developed diagnosis tool should facilitate in linking these two aspects (arrow (3) in Figure 2.3). The next section presents a commonly used tool for facilitating diagnosis of the average lateness: the throughput diagram.

2.3. Diagnosis tool: the throughput diagram

The throughput diagram is regarded as a useful tool to facilitate diagnosis of performance in terms of the average lateness (Wiendahl, 1988). It presents the cumulative input and output of work of a particular capacity group across time. The usefulness of plotting cumulative input and output related to arrivals and completions of jobs across time was already proposed by Conway et al. (1967). Later, plotting the number of jobs has been replaced by the more general work content unit in a diagram known as the throughput diagram. The general layout of a throughput diagram is shown in Figure 2.4.

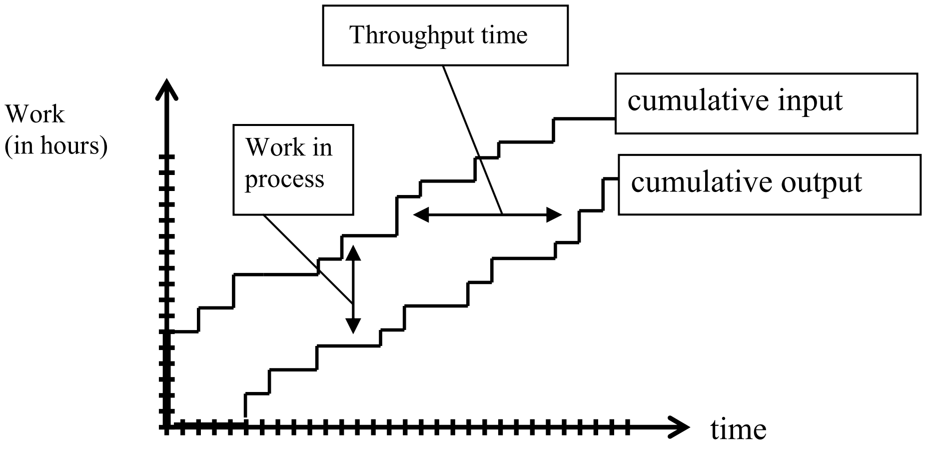

Figure 2.4. The basics of throughput diagrams.

The horizontal axis in a throughput diagram shows cumulative time in working days. The vertical axis shows work measured in processing time hours for a capacity group. When for example an order arrives that needs 20 hours of work on a capacity group, the input curve increases with 20 hours at the time of arrival. The cumulative output curve increases by the hours of work completed for a capacity group at the time of completion. The vertical distance between the two curves depicts the work-in-process (WIP) and the horizontal distances relate to average throughput times. Only for First Come First Served (FCFS) discipline the horizontal distances indicate the throughput times of individual orders.

A throughput diagram can help to gain insight into the causes of the average lateness. When due dates are set, the average lateness can only be controlled by controlling average throughput times. Controlled average throughput times are indicated by parallel input and output curves in the throughput diagram. An observed deviation of this ideal situation may have many causes. We confine ourselves to deviations caused by PPC decisions. Facilitating diagnosis and linking performance to PPC decisions requires drawing a throughput diagram with multiple input and output curves. This will be shown for a case of an MTO company. The company concerned produces plastic products and components. It consists of two departments. Department 1 mainly performs material removal operations, like sawing, milling and laser cutting. Department 2 performs more labour intensive work like cleaning, bending, gluing and assembling. For each relevant capacity group throughput diagrams with multiple input and output curves have been constructed. This paper focuses on the throughput diagram related to the laser cutting machine (Figure 2.5). For orders visiting the laser cutting machine, five relevant stages can be distinguished. So the throughput diagram consists of five input and output curves, all in terms of laser cutting hours.

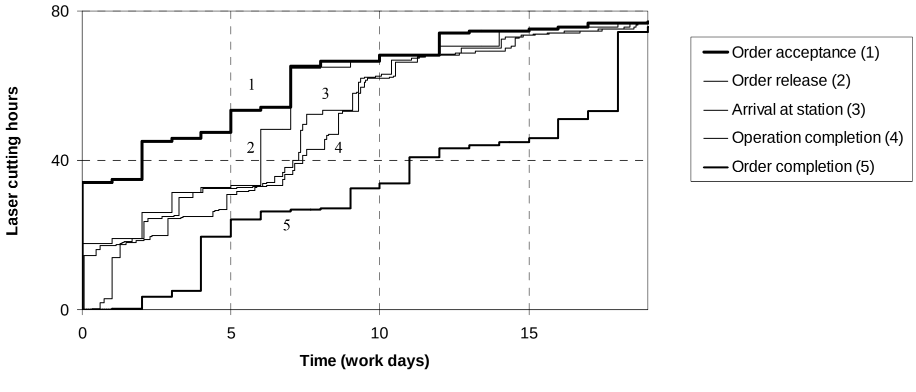

Figure 2.5. Throughput diagram with multiple input and output curves

The horizontal axis in Figure 2.5 shows time in working days. Day 0 is the day at which the measurements started. The vertical axis shows cumulative hours of load for the laser cutting machine. The upper two curves (1, 2) are respectively the order acceptance and the order release curve. These curves increase at respectively the time of acceptance and the time of release with the amount of load the order imposed on the laser cutting machine. The third and fourth curves represent order arrival at laser cutting and completion of the operation respectively. The fifth curve is the order completion curve. This last curve increases when the full order is completed, but is also measured in laser cutting processing hours.

The horizontal distance between order acceptance (1) and order completion (5) relates to total throughput time. When we look at the total throughput time in the diagram we can see that average throughput times relating to work accepted between day 6 and 8 are longer than for work accepted before day 6. This has a negative influence on the average lateness, supposing the average promised delivery times did not increase. The throughput diagram can now help to unravel the causes of these increased throughput times.

First of all Figure 2.5 shows that average throughput times at the laser cutting machine itself are relatively well-controlled (curve 3<>4), but are increasing in downstream capacity groups (curve 4<>5). If we look at the distance between acceptance and release, the so-called pool time (curve 1<>2), we can see that from day 7 on the distance between these two curves disappears. This implies that accepted orders are released almost directly from that time on, while before day 6 the orders were released much more selectively. We can see that the laser cutting machine could cope very well with such an increase by speeding up operation completions. However, with the help of this diagram it could be detected that the variable output of the laser cutting department caused increasing loads for downstream operations, with throughput times increasing correspondingly. In such a way control of average throughput times, one of the prerequisites for a low average lateness, could be linked to the release decision.

Besides being influenced by control of average throughput times, the average lateness also depends on promised due dates. To link the average lateness to problems caused by the promising of due dates for orders, we have to draw a curve of promised output (see Figure 2.6). For clarity we leave out curve 2, 3 and 4 of Figure 2.5. The promised output curve (6) represents the cumulative amount of laser cutting hours that are promised to customers. The promised output curve (6) increases stepwise at the due dates of orders. First we can see in Figure 2.6 that the time between acceptance of orders

(1) and promised output (6) decreases in time. We can also see - when comparing the promised output curve (6) to the order completion curve (5) – that from day 14 more hours of laser cutting work had been promised than were actually completed. This indicates that on average due dates had been set too tight.

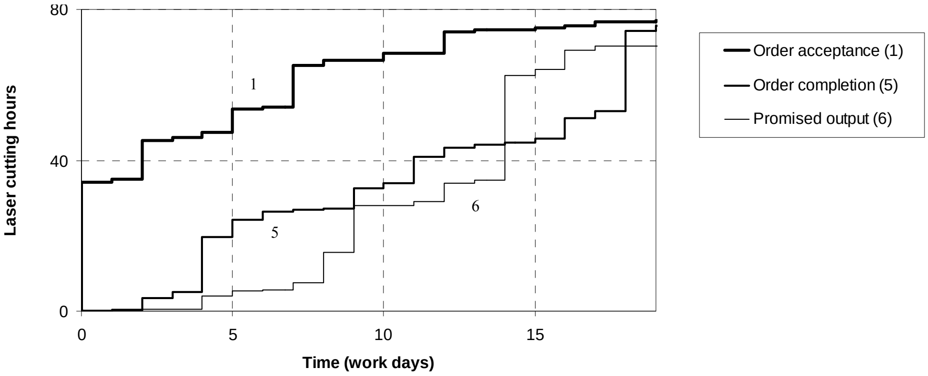

Figure 2.6. Throughput diagram including promised output curve.

These examples show how throughput diagrams can be useful to facilitate a diagnosis related to the average lateness. With some extensions throughput diagrams can also visualize the deviations of due dates for individual orders (Wiendahl, 1988; Wiendahl, 1995). With the help of an extended throughput diagram we can analyse which type of orders have been completed late in terms of orders with either short or long processing times or orders visiting certain capacity groups. By using multiple throughput diagrams consisting of different capacity groups we may trace back the progress of orders. However, doing this for only one order is already difficult and time consuming to accomplish and overview is easily lost. Therefore an extended throughput diagram is not helpful in tracing back the progress of large sets of orders.

This section has briefly shown how the throughput diagram can be a useful tool for facilitating the diagnosis of the average lateness. With the help of the throughput diagram, the average lateness of orders can be explained. However, its support for the diagnosis of the variance of lateness is limited. Therefore the next section presents a newly developed tool, with an explicit focus on facilitating diagnosis related to the variance of lateness.

2.4. The order progress diagram

The newly developed tool helps to explain the variance of lateness by relating the lateness of individual orders to the progress of these orders and to the input and output control decisions affecting this progress.

Starting point for facilitating diagnosis is a scatter diagram depicting each delivered order as a dot (see Figure 2.7). This order scatter diagram consists of 20 randomly selected orders of the case company. Again day 0 is the day on which the measurements started. The horizontal axis shows the realised delivery date, the date an order is completed and the vertical axis shows the lateness of an order, measured in days. All dots above the horizontal axis are orders that are completed later than planned, while dots below this axis represent orders completed earlier than planned. In this diagram we see that some orders are on the horizontal axis, some are above and some are below, which reflects the variance of lateness. From this diagram we cannot trace the causes of this variance yet. We would like to indicate the causes why some orders are late, while others are delivered much too early. For this reason we extend this order scatter diagram to a so-called order progress diagram.

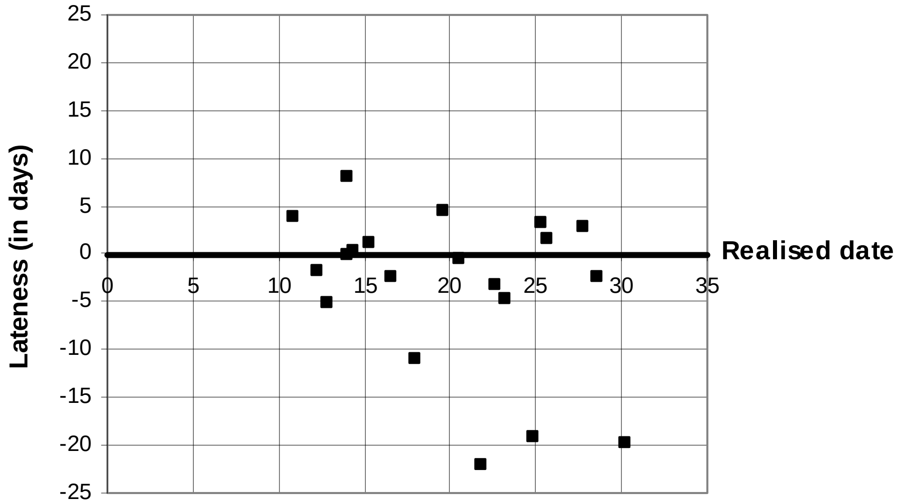

Figure 2.7. Order scatter diagram.

The order progress diagram indicates the difference between the progress of an individual order and the average order progress pattern. Thus, we can observe which orders are delayed and which are speeded up for each stage of the order. Besides, we will signal the extent of delay or speeding up and relate it to the estimated lateness. For each stage of the order the diagram shows the relationship between realised individual throughput times and average throughput times. Calculating backwards from the delivery date of an order, 'virtual' due dates are set per stage by subtracting average throughput times of the next stage (see Figure 2.8). For example, the virtual due date (VDD) of laser cutting for this order is calculated by subtracting the average throughput time (ATT) of gluing from the delivery date (DD) of the order.

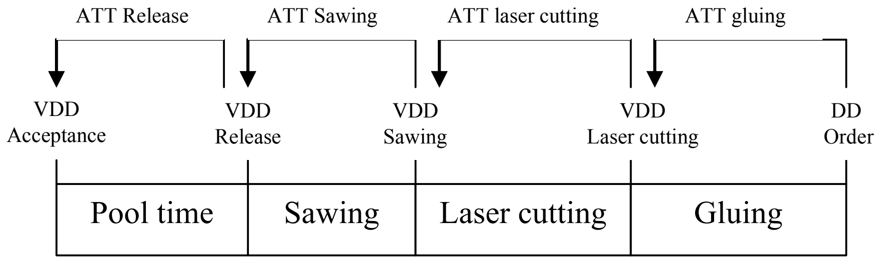

Figure 2.8. Calculation of due dates.

For reasons of clarity the order progress diagram is illustrated here for a reduced set of only 4 orders (see Figure 2.9).

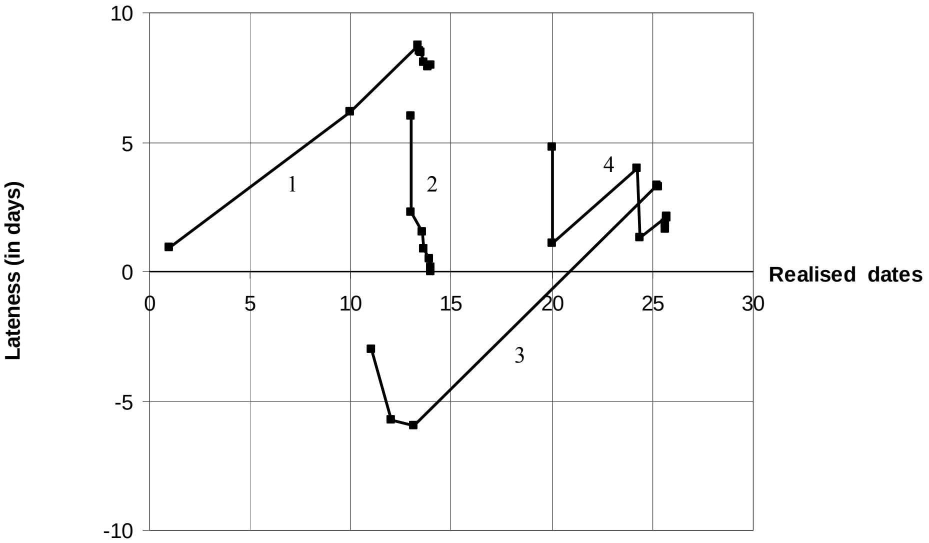

Figure 2.9. Order progress diagram.

The horizontal axis in Figure 2.9 shows realised dates for different stages of the process in terms of working days. Day 0 is the day at which we started measuring. The vertical axis shows (estimated) lateness in different stages of the process. The estimated lateness after each stage is defined as the difference between the realised completion date of that stage and the virtual due date of that stage. Estimated positive or negative lateness after completing a certain stage means that an order will be delivered respectively late or early if throughput times in later stages are equal to average throughput times for those stages.

The progress of an individual order is represented by a single curve. The right end dots of the four curves in Figure 2.9 are the same as the dots in Figure 2.7. Other dots in a curve represent operation completion dates of a particular stage with a corresponding estimated lateness at the time of completion. In an ideal situation all dots lie on the horizontal axis. If all dots lay on the horizontal axis, estimated lateness after completing every stage would be zero and no variance between orders would exist. The upward or downward direction of each line segment in the curve represents respectively an increase or decrease of estimated lateness of the order in that particular stage.

An order progress diagram gives insight into the progress of orders and the link with control decisions. The vertical distance between the starting point of the curve and the horizontal axis shows the estimated lateness of an order at the time of acceptance, i.e.

the resulting lateness if all stages would require exactly the average throughput time. If the acceptance dots are widely spread around the horizontal axis, this may indicate a first cause of a high variance of lateness. It means that some accepted orders will require very short throughput times per stage (for example, order 1 and 4), some may have longer ones (for example, order 2 and 3). However, individual throughput times can still be corrected by successive input control decisions.

The second dot in each curve represents the release decision. Order release can influence estimated lateness by varying the time between acceptance and release, the so-called pool time. This means that orders that have a positive estimated lateness at the time of acceptance must be released relatively quickly and vice versa. For example release of order 2 and 4 in Figure 2.9 takes place directly upon acceptance for this reason. This may help to reduce the variance of lateness. However, the release timing for order 1 and 3 may increase the variance of lateness. Order 1, which is estimated to be delivered late at the time of acceptance, is further delayed by release, while order 3 is release relatively quickly, though it is estimated to be delivered early at the time of acceptance.

We can also observe the progress of orders after they have been released to the shop floor. We can see whether orders are delayed or speeded up in certain stages of the process by comparing the angles of the line segments to a horizontally drawn line. If the line segment of a stage is heading upwards, realized throughput times are longer than average throughput times in that stage and vice versa. For example in Figure 2.10 we can see that the last stage of the order is sloping upwards. This means that the progress of this order is slowed down in the last stage, which finally resulted in the order to be delivered late.

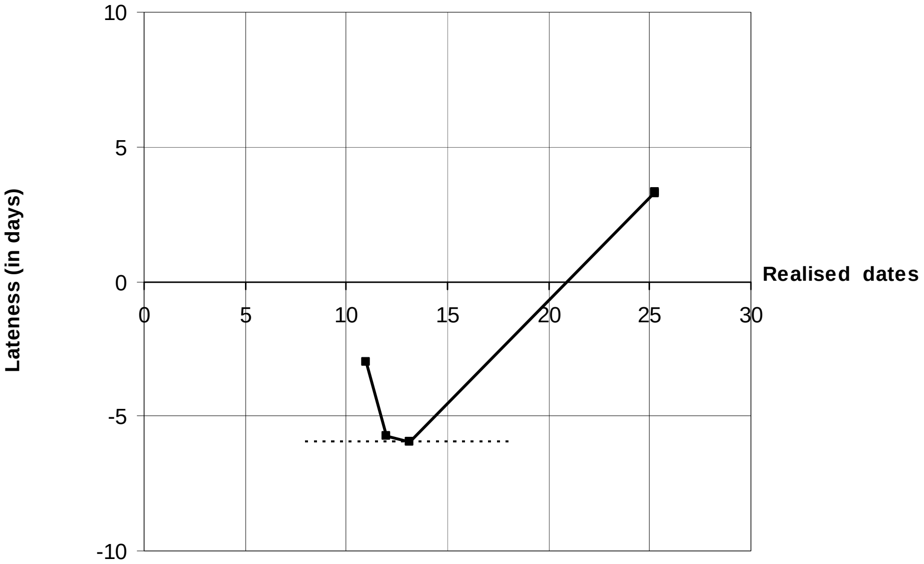

Figure 2.10. Order progress in a particular stage.

Upward and downward sloping line segments could be caused by the applied dispatching rules or output control decisions in the considered stage. We may want to retrieve at which capacity groups priority dispatching seems inconsistent with delivery performance requirements. To relate the influence of priority dispatching at a capacity group to the variance of lateness, an order progress diagram containing only throughput times of that particular capacity group can be drawn or related segments can be highlighted.

Figure 2.11 shows for example the throughput times of orders in the sawing department. The first and second dots in every line segment represent the estimated lateness of an order at the arrival and the completion in the sawing department respectively. If the variance of lateness of orders in the sawing department was decreased, orders would converge to the horizontal axis. To achieve a decrease of the variance of estimated lateness, higher priority should be given to orders with an estimated positive lateness than to orders with an estimated negative lateness. In that respect we can see for example that orders 1 and 2, which arrived at the sawing department and were expected to be delivered late, were speeded up in the sawing department. On the other hand orders 3 and 4, also expected to be delivered late, were slowed down. At the same time that order 4 was slowed down in the sawing department, order 5 was processed. However, this order had a virtual due date of sawing far into the future. A number of such examples may indicate poor priority dispatching at sawing and require further investigations.

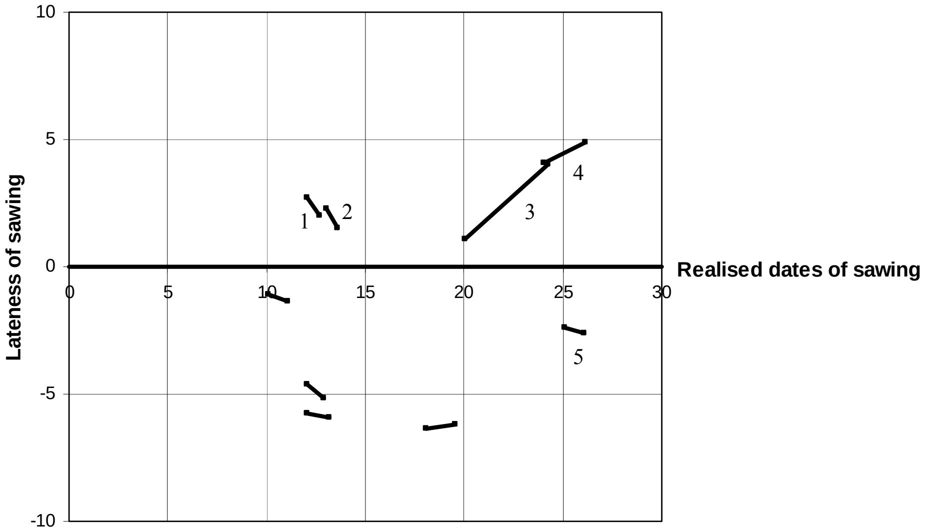

Figure 2.11. Order progress in the sawing department.

This section has presented the development of the order progress diagram and its use for facilitating the diagnosis of the variance of lateness. By means of a case we have illustrated how the order progress diagram helps in tracing delivery reliability performance back to the progress of individual orders and to PPC decisions affecting this progress. The next section concludes this paper.

2.5. Conclusions

Delivery reliability is one of the order winning performance criteria for many MTO companies. Managers are increasingly faced with the need to improve their delivery reliability performance. The resulting need for diagnosis tools has been the starting point for this paper. A key principle for a good diagnosis tool is the ability to trace back the observed performance to relevant PPC decisions. A very powerful tool identified in literature that supports this key principle is the throughput diagram. In this perspective we have investigated the capabilities of the throughput diagram by means of industrial data. The research shows that the throughput diagram is particularly helpful in tracing back the performance to decisions of input and output control performance, and that it concentrates on the influences on the average lateness. But this tool provides only limited support for tracing the causes of the variance of lateness. Nevertheless, a good performance on both the average lateness and the variance of lateness is necessary for high delivery reliability, as an order delivered early cannot compensate for an order delivered late.

In the second part of this research a new tool, the order progress diagram, has been developed that focuses on the variance of lateness. By means of the industrial data it has been demonstrated how the order progress diagram helps to link PPC decisions to progress differences among individual orders. Order progress is observed in different stages of the process, from order acceptance until completion. Calculating backwards from the delivery date of an order, it compares the realised throughput time of an order with the average throughput time for each stage of the process. Thus, it indicates where orders have been speeded up or slowed down, and identifies the final consequences for the distribution of lateness among orders. While keeping track of individual orders, in terms of variance, an aggregate view on the whole set of orders is maintained. The visual presentation of the order progress diagram enhances insights into which PPC decisions are and which are not consistent with delivery reliability requirements. Because the diagram clearly indicates in which stage counterproductive decisions are taken, it provides a good starting point for finding suitable strategies to improve the delivery reliability performance of companies.

Future research will focus on gathering additional empirical results to enable further enhancement of the order progress diagram. Also its use as an online monitoring tool will be investigated.