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Measuring Throughput Times in Wood Component Production: A Case Study

Sven-Vegard Buer (✉), Oladipupo Olaitan and Jan Ola Strandhagen

Department of Mechanical and Industrial Engineering, NTNU,
Norwegian University of Science and Technology, Trondheim, Norway
sven.v.buer@ntnu.no

Abstract. An increasing number of manufacturing companies acknowledge the importance of flow efficiency. As an important key performance indicator in lean implementation processes, being able to measure the throughput time of products is important to assess the current situation. This paper presents a stepwise method for measuring the throughput time in manufacturing environments with no unique identification of products, products made up of several levels of subcomponents, as well as varying batch sizes throughout the process. With relatively few data points, the method calculates the average throughput time of products for a chosen time period. The method is applied to a case company who manufactures wood components.

Keywords: Throughput time, Performance measurement, Production planning and control.

1 Introduction

Lean manufacturing highlights the importance of flow efficiency rather than resource efficiency, which traditionally has been the focus for manufacturing companies. While resource efficiency emphasizes local optimization, flow efficiency rather focuses on minimizing the throughput time for a product through the system.

To support lean improvement projects, it is important to have accurate and responsive key performance indicators (KPIs). Lean improvement projects typically aim to improve operations in one or more performance dimensions; therefore, establishing relevant KPIs is important to give decision makers feedback on the current state and the effect of the improvement initiatives. While some KPIs are easy to extract from the operations, for instance through existing IT systems, others require more effort from employees to gather the data and calculate the value.

An important KPI in lean manufacturing implementations is the throughput time of products [1]. This gives an accurate measure of the current performance of the company regarding their efforts to streamline the production and eliminate waste and waiting times along the value chain. While it is easy to measure throughput time in a situation where products are allocated unique IDs, for instance, a barcode or RFID chip, securing accurate throughput time measurements in a situation without individual identification of components and varying batch sizes throughout the manufacturing process can be a challenge.

Despite the increased popularity of IT systems in manufacturing companies, through the adoption of Industry 4.0, many still only have basic transaction and IT systems. Motivated by the challenges of such companies, this paper presents a method for measuring throughput times in an environment without individual tracking of components and varying batch sizes. The rest of the paper is organized as follow: Section 2 provides a background of the case company and reviews the literature on methodologies for estimating throughput time, while Section 3 describes the calculation method that has been utilized in this study. Section 4 presents the results from the throughput time analysis in the case company. Findings from the results are then discussed in Section 5, followed by conclusions and recommendations for future work.

2 Theoretical Background and Overview of Case System

Flow is one of the five lean principles as described by Womack and Jones [2]. A central aspect of lean is to shift the focus from resource efficiency to flow efficiency [3]. Product flow efficiency concerns keeping the product moving through the production process [3], and this is mainly achieved through an eradication of all forms of production waste [2] and a tight synchronization between the upstream and downstream stages of a production system [4]. The obvious benefits of keeping continuous flow are that it shortens the system throughput time and increases the responsiveness of the system to the fulfillment of customer orders. However, it is generally difficult to quantify the improvements derived from the implementation of lean, particularly because lean encompasses various elements and involves company-wide changes. It is difficult to isolate and quantify the improvements that are due to individual elements. Ironically, the company-wide changes required by lean means that a preliminary quantification of the level of improvement to expect from its implementation is necessary to convince an organization to invest resources in it.

Lean's ability to achieve shorter throughput time is one of its most easily attributable benefits. Lean threats inventory as waste and aims to eradicate it [2], and, based on Little's law, lower inventory level should shorten the throughput time [5]. Even though the relationship between throughput time and other parameters of the system that are often targeted by a lean implementation is clear as expressed in Eq. (1), the approach to estimating those parameters for a system produces different results.

$$L = \lambda\mu \tag{1}$$

where:

L is the number of items in the system (i.e. inventory level)
λ is the average number of items arriving per unit time (i.e. arrival rate)
μ is the average waiting time in the system for an item (i.e. throughput time)

While the original equation defines λ as the arrival (or input) rate into the system under consideration, a subsequent study has represented it as the departure (output) rate from the system [6]. In a system with a steady flow, the use of either definition should produce similar estimates of throughput time [7]; however, this would not be the case if there were conditions that significantly impact the steady flow of items through the system. Little and Graves [7] highlight two conditions that need to be valid in order to use output rate instead of input rate for calculating throughput time. First, there needs to be conservation of flow (steady state). Second, all jobs that enter must also be completed and exit the shop. Other factors that could result in discrepancy between the use of input and output rates are fluctuations in system inventory, variability in system capacity, the presence of assembly or batching operations in the system, highly variable product routing and the application of prioritization rules or order release mechanisms that significantly alter the flow of items within the system.

This study uses input and output rates to estimate the throughput time for a case company, which specializes in the manufacture of internal and external (visible) wood components. The company operates with modern machinery for processes such as wood planing, gluing, cutting, sanding, machining and lacquering. In addition, they operate manual assembly stations and an automated robot assembly cell. They operate on an order-driven basis and, therefore, do not have a finished goods inventory. Instead, the customer order decoupling point (CODP) is located at a supermarket (i.e. a buffer for holding semi-finished parts) close to the end of the manufacturing process. Whenever there is an incoming order, parts are picked from here and lacquered (only for visible wood) and assembled before being shipped directly to the customer. In order to map the current state of the case company regarding material and information flows, the control model methodology by Alfnes and Strandhagen [8] was used. This AS-IS mapping of the company provided valuable insights into the current situation and helped to identify which data points were available for use. Fig. 1 illustrates a simplified control model for the case company, focusing on the process investigated in this study.

The application of input and output rates to estimate throughput time for this case company should give insights into the extent to which the factors earlier described would influence the reliability of using either approach. In the following section, both methods are described, followed by their application to the case company. The section also gives insights into the process of translating raw data into the KPIs that are needed to evaluate the progress made when undertaking system improvement programmes.

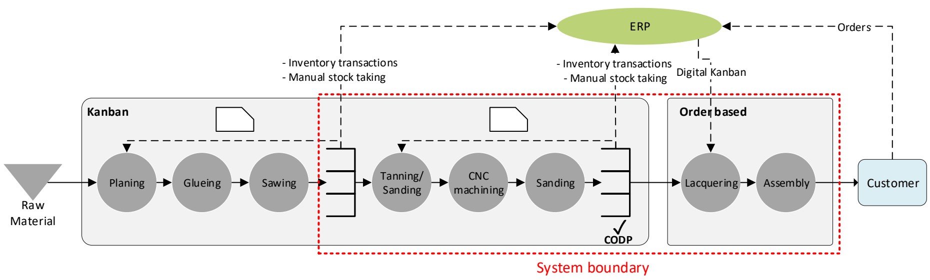


Fig. 1. Simplified control model of the process for product family Z

3 Throughput Time Measurement Method

This section will give a step-wise introduction to the applied throughput time measurement method that is suggested and used in the presented case. To use this method, the required data inputs are: i) the amount of work-in-process (WIP) for each product family (including sub-components), ii) the output (sales) and/or input for each product family in a chosen time period, and iii) number of working days in the chosen time period.

Step 1: Define the system boundaries

The first step in calculating the throughput time is to decide on the boundaries of the system in which the throughput time should be measured. This means to look at specific parts of the value stream and/or specific products [9]. In a general case, it would be beneficial to have a holistic view and look at the whole manufacturing system, but in special cases, there might be reasons for looking at specific parts of the manufacturing process. This could, for instance, be in cases where there have been improvement projects in a specific department, but the throughput time through this department is so small compared to the total throughput time that the improvements can be difficult to observe. The selection of the system boundary will also depend on the available data points. In order to use the method, data is needed about input or output rate and the level of WIP. For instance, in a situation where only the WIP is known for parts of the process, it would be necessary to alter the system boundary to only consider this part.

Step 2: Use the bill of materials to calculate the "longest" value stream

If a product consists of assembled components, it is essential to adjust its contribution to the WIP, based on the individual contributions of its components. Therefore, based on the bill of materials (BOM), which specifies the relationship between the end product and the components, the WIP for each component should be converted into a corresponding number of end products. Following this, the "longest" value stream should be calculated by adding up the number of end products and the component which have the largest WIP in "end product" units. This approach is similar to the calculations of Manufacturing Critical-path Time, known from Quick Response Manufacturing [9].

Step 3: Calculate average throughput time for a chosen time period

Some general notations are outlined below:

$TT_{i,p}$: Average throughput time for product, *i*, through the defined system boundaries in period, *p*

WIP_i: Current WIP of product, *i*, in the defined system boundaries (in number of products)

$O_{i,p}$: Output (sales) of product, *i*, in period, *p*

$OR_{i,p}$: Output rate for product, *i*, through the defined system boundaries in period, *p* (in number of products per time unit)

$I_{i,p}$: Input of product, *i*, into the production process in period, *p*

$IR_{i,p}$: Input rate for product, *i*, through the defined system boundaries in period, *p* (in number of products per time unit)

WD_p: Number of working days in period, *p*

Eq. (2) calculates the output rate by dividing the output in the period by the number of working days in the same period.

$$OR_{i,p} = \frac{O_{i,p}}{WD_p} \tag{2}$$

Similarly, Eq. (3) can be used to calculate the input rate.

$$IR_{i,p} = \frac{I_{i,p}}{WD_p} \tag{3}$$

As explained in Section 2, Hopp and Spearman [6] argue for using the output rate of the system to calculate the throughput time of the selected product(s) within the selected system boundary. The method is shown in Eq. (4).

$$TT_{i,p}(OR) = \frac{WIP_i}{OR_{i,p}} \tag{4}$$

On the contrary, Little [5] argue for using the input rate, as shown in Eq. (5).

$$TT_{i,p}(IR) = \frac{WIP_i}{IR_{i,p}} \tag{5}$$

By combining Eq. (2) and Eq. (4), or Eq. (3) and Eq. (5) alternative versions of the formula are obtained as shown in Eq. (6) and Eq. (7), respectively:

$$TT_{i,p}(OR) = \frac{WIP_i \times WD_p}{O_{i,p}} \tag{6}$$

$$TT_{i,p}(IR) = \frac{WIP_i \times WD_p}{I_{i,p}} \tag{7}$$

4 Applying the Method at the Case Company

This section describes how the proposed methodology was used in the case company to calculate the throughput times for a family of products. This section will follow the step-wise method described in the previous section. We focused the analysis on a specific product family, from here known as product family Z. The BOM for product family Z is presented in Fig. 2, while its sales in 2016 are presented in Table 1.

Table 1. Sales of product family Z in 2016

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
820	1036	714	792	656	653	153	588	735	493	1128	266

Step 1: Define the system boundaries

The case company did not have any data available regarding the inventory level at the raw material inventory or the amount of WIP from the raw material inventory up until the first intermediate inventory (supermarket). Based on this constraint, it was therefore chosen to define the system boundary from the first supermarket up until products are delivered. In addition, up until the first supermarket, the material is not assigned to a specific product family, which complicates the process of assigning product family specific throughput times. The system boundary is illustrated in Fig. 1.

Step 2: Use the bill of materials to calculate the "longest" value stream
The case company does not continuously keep track of their WIP levels. Although they utilize a Kanban control system internally in production, which limits their maximum WIP, there will still be variations in WIP because of uneven demand, replenishments at different times and products being scrapped. Also, there is still a large discrepancy between the registered WIP and the actual WIP, even though material transactions are supposed to be registered in the ERP system. This is confirmed by quarterly stocktakings. Therefore, in this case, the WIP recorded from the stock takings shown in Table 2 were used as input data. However, if they are able to increase the compliance between the ERP system and the actual inventory levels, using the WIP data from the ERP would provide a more accurate and responsive solution than using the stock taking data.

By going through their historical data, and using the calculation method described in Section 3, it became clear that the component which created the "longest" value stream tended to change between each time. This is normal and related to the WIP variations in the Kanban system described above. If there was a trend that there was always a specific component causing the "longest" value stream, it would have been a sign that the Kanban bin size or the number of Kanban cards should be adjusted for this component.

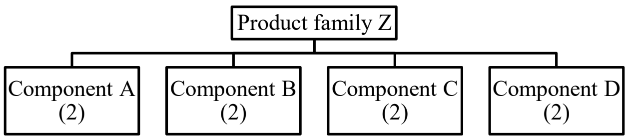


Fig. 2. The BOM for the investigated product family Z.

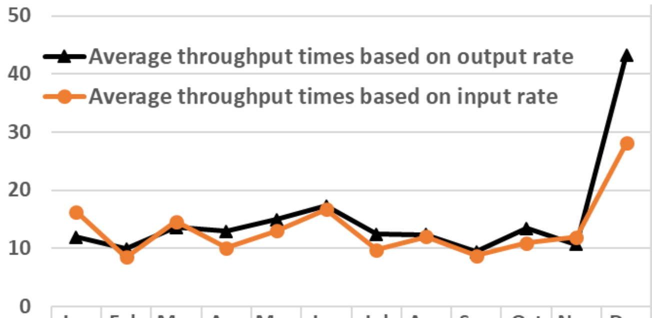
Table 2. The results of the stocktakings in 2016

	March	May	September	December
Product family Z	136	104	84	164
Component A	564	383	449	768
Component B	495	818	345	581
Component C	703	786	281	665
Component D	410	781	462	655
Total for the "longest" value stream*	487	513	315	548

**In number of end units*

Step 3: Calculate average throughput time for a chosen time period
By using the collected data, we calculated the average throughput time for each month for the investigated product family Z. As visible in Fig. 3, there is a huge spike in December. This was caused by a reorganization at the company's main customer, which led to a large decrease in demand that month. Since they operate on an order-driven

basis, this naturally affected the output rate, which again led to an increase in the throughput time. The figure also shows that the calculated average throughput times are typically higher when using the output rates as the basis for the calculation. This is because, in most cases, the input is larger than the output of a process because of scrap during the production. However, one example of a situation where the input is smaller than output is in periods where the WIP is reduced.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average throughput times based on output rate	11.9	9.9	13.6	12.9	14.9	17.3	12.4	12.3	9.4	13.4	10.7	43.3
Average throughput times based on input rate	16.3	8.5	14.6	10.1	13.0	16.7	9.7	12.0	8.7	10.9	11.9	28.1

Fig. 3. Calculated average throughput times for product family Z in 2016 (in working days)

5 Findings, Conclusions, and Recommendations

The case company have carried out several initiatives to continuously lower the throughput time. However, they lacked a system for measuring the throughput time of products based on their current data gathering points. The method described in this paper is adapted to their needs and provides an updated KPI to measure the effect of their future improvements, both minor and major.

The method is not able to track the exact throughput time of specific products; however, its accuracy increases with the accuracy of the amount of WIP. For production systems that operate with a batch size larger than one, there is a natural variation in WIP and the specific throughput time will naturally vary between the first and the last part of the batch or lot. In such situations, it can be argued that the average time for the batch is of more interest than tracking individual orders.

This paper provides theoretical reflections as well as empirical data regarding the choice between input rate and output rate in throughput time calculations. For manufacturing environments that are similar to that studied here, we propose that using the output rate is the preferred choice. One reason is that output rate is more reflective of ongoing challenges in the system, which might result from issues such as blockage, scrap or reworks. For instance, as observed in Fig. 3, the throughput time estimated using the output rate was more reflective of the challenges the company faced during the December period. Because of reorganization by the customer downstream, the sales volume and, therefore, the output rate reduced, but the input rate did not reduce correspondingly. Another reason is that of simplicity; it is easier to measure the output rate of a single end item rather than the input rates of its many components.

This paper presents a method for measuring throughput time of products, illustrating its use through a case of a wood component producer. Although the method in itself is not novel, as it draws on well-known and established formulas, the paper presents a stepwise description of the calculation method. The contribution of the paper lays here, assisting practitioners in adapting the basics of Little's law to measure the throughput time of their production system, in addition to comparing the use of input and output rate. The basics of Little's law helps to highlight the fact that a reduction of cycle and setup time in most cases will not have a strong effect on the throughput time. This is because products usually spend most of their time in inventory. However, reducing the cycle and setup time will have an indirect effect since it increases the responsiveness of the manufacturing system, allowing for reducing the inventory levels without necessarily lowering the service levels.

Future research should investigate the effect of using a rolling horizon (e.g. last 30 days) instead of fixed intervals (e.g. months) on the quality of the results.

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References

1. Duque, D.F.M., Cadavid, L.R.: Lean manufacturing measurement: the relationship between lean activities and lean metrics. Estudios gerenciales 23, 69-83 (2007)
2. Womack, J.P., Jones, D.T.: Lean thinking: banish waste and create wealth in your corporation. Simon and Schuster, London (2003)
3. Modig, N., Åhlström, P.: This is lean: Resolving the efficiency paradox. Rheologica, London (2012)
4. Ohno, T.: The origin of Toyota production system and kanban system. International Conference on Productivity and Quality Improvement, pp. 3-8. Industrial Engineering and Management Press Atlanta, GA (1982)
5. Little, J.D.C.: A Proof for the Queuing Formula: $L = \lambda W$. Operations Research 9, 383-387 (1961)
6. Hopp, W.J., Spearman, M.L.: Factory physics: foundations of manufacturing management. Irwin McGraw-Hill, Boston (2001)
7. Little, J.D.C., Graves, S.C.: Little's Law. In: Chhajed, D., Lowe, T.J. (eds.) Building Intuition: Insights From Basic Operations Management Models and Principles, pp. 81-100. Springer US, Boston, MA (2008)
8. Alfnes, E., Strandhagen, J.O.: Enterprise design for mass customisation: The control model methodology. International Journal of Logistics: Research and Applications 3, 111-125 (2000)
9. Suri, R.: It's about time: the competitive advantage of quick response manufacturing. Productivity Press, New York (2010)