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S-DBR: A PPC Approach Beyond Bottleneck Scheduling

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Abstract

Practice has traditionally led theory in operations management and particularly production planning and control (PPC). This can be seen in the work of Ford, Deming, Ohno and Goldratt. These developments have in turn challenged academic understanding and the need for theory that encompasses a systems approach. However, the academic research process tends to encourage specialist study rather than holistic investigations needed to extend these seminal developments. At a general level this paper aims to clarify the critical need to appreciate, challenge, and contextualize the adopted PPC methodologies, identifying the common need for flow management signaling tools that focus improvement activity. More specifically the paper will illustrate this through the application of a seminal TOC development entitled Simplified-Drum-Buffer-Rope (S-DBR). Research into TOC has largely been confined to distinctive elements, such as bottleneck scheduling with little attention being given to its underlying philosophy, concepts, and wider signaling tool and associated embrace empowerment. To address this gap, we attempt to unpack the philosophical layer of S-DBR with particular focus on the concept of flow and human empowerment. This is followed by a case review on an S-DBR implementation, demonstrating how the tools in S-DBR: planned load (PL) and buffer management (BM) were contextualized to engage, upskill, and empower personnel. To the best of our knowledge, this is the first reported S-DBR study in which the researcher was also the intervention implementer in the case company.

Keywords
Simplified Drum Buffer Rope, Production Planning and Control, Theory of Constraints, Human Empowerment, Buffer Management.

1. Introduction
It was reported in recent reviews that organizations continue to experience high failure rates in introducing production planning and control (PPC) related process improvements (McLean et al., 2017). This has drawn the attention of academics to identify the failure factors. Some researchers attributed the failure factors to project management related issues, such as organization culture, leadership, resistance to change, communication, and other soft factors (Antony et al., 2023; Bader et al., 2024). However, there are other researchers, such as Hopp (2018) who attributed the failures to the cherry-picking of tools associated with PPC methodologies without a deeper understanding of its philosophy.

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For example, the theory of constraints (TOC) based PPC application requires both the bottleneck scheduling and buffer management (BM) to work together. However, it is often being reduced to a mere bottleneck solution (see Boer et al. 2015; Schmenner and Swink 1998:101; Spearman, 1997). The order release concept in TOC based PPC applications such as OPT (Optimized Production Technology), DBR (Drum-Buffer-Rope), and S-DBR (Simplified Drum-Buffer-Rope) are generically referred to as bottleneck mechanism by academics (Roderick, Phillips, and Hogg 1992; Bergamaschi et al. 1997) or theory of bottleneck in operations management (Boer et al. 2015). The buffer management (BM): a time-based signaling mechanism used to realize pull mechanism in TOC is largely ignored by academics. While BM is a critical element within TOC, just as Kanban is to the Toyota Production System (TPS), the reductionist approach by researchers on TOC has under-appreciated not just the tools, but also the human empowerment element advocated in TOC approaches and applications.

1.1 Objectives

The aim of this paper is to use a TOC focused case study to demonstrate the need to take a holistic approach to developing PPC solutions to meet specific business needs. To achieve this the paper firstly develops an understanding of the key perspectives of TOC on PPC. Secondly, to review how these perspectives are realized through S-DBR and its associated tools. Finally, to understand the necessary adaptation needed in this real-world implementation.

To achieve these objectives, this paper is organized as follows. In the literature review, the two key perspectives of TOC on PPC: flow management and human empowerment will be explored. This is followed by reflecting how these perspectives are substantiated through S-DBR and its associated tools: Planned Load (PL) and Buffer Management (BM). The subsequent sections focus on a case study where S-DBR was successfully implemented as an intervention. The results and discussion will focus on the necessary adaptation needed to meet contextual requirements. This paper ends by reflecting on the wider implications of this case study and potential direction for future research.

2. Literature Review

2.1 Wider Operations Theory

Boer et al., (2015) identifies the higher-level theory of swift and even flow, performance frontiers (Schmenner and Swink, 1998) and TOC (Goldratt, 1990; 2011) that clarifies the importance of managing system flow and the systematic reduction of variability and uncertainty. However, linking this theory with practice requires deeper insight that links the seminal developments of Ford, Ohno and Goldratt. These seminal developments address different levels of variability and uncertainty which demand distinct tools. In the case of TPS, kanban largely fulfilled this role, but TOC addressed the increased system complexity by focusing on constraints and the use of aggregated buffers. These two concepts embrace all TOC applications but as with kanban signaling, need to take on distinct forms to meet the needs of different applications.

The importance of flow and variability has long been acknowledged in queuing theory (line theory) effectively interpreting the importance in the practice embraced in CONWIP (Hopp and spearman, 1997) where one in one out ensures lead time stability, but does not address the opportunity to manage such buffers as advocated in TOC and exploited in this case implementation which is particularly important in more unstable environments.

2.2 TOC in perspective

TOC originated from practice as Optimized Production Technology (OPT) software in the 1970s by Goldratt (Bylinski, 1983). The underpinning philosophy of OPT was captured in his book “The Goal” (Goldratt and Cox, 1984); and is a recognized theory in operations management in the academia (Boer et al., 2015; Gupta and Boyd, 2008). It adopts the view that the primary objective of the PPC is to improve the system flow (Goldratt, 2009). A similar perspective can be seen in other industry best practices such as the Ford and Toyota Production System (Lean), where the main purpose of improvement initiatives in PPC is to improve the flow of value (Womack et al., 1990: 23 – 68).

Different mechanisms have been introduced in these practices to realize flow management and continuous improvement. For example, to minimize overproduction and congestion, Ford uses direct observation on available space, Toyota Production System (TPS) / Lean uses inventory level (Kanban), and TOC uses time (buffer management) to realize a pull system which explicitly limits the level of work-in-progress (WIP) in the system (Goldratt, 2009; Hopp and Spearman, 2004). The associated continuous improvement practices, such as Deming’s quality management, waste reduction in Lean, and the five focusing steps in the TOC share the common primary objective of improving the system's flow. As illustrated in the theory of swift and even flow, "the more swift and even the flow of materials through a process, the more productive that process is" (Schmenner and Swink, 1998:102).

The TOC views a constraint as a limiting factor that ultimately determines the systems flow rate and throughput. Excellence in system performance is achievable by focusing on managing system constraints (Goldratt and Cox, 1984). The much-explored Drum Buffer Rope (DBR) application generally assumes that the constraint (the drum) is an internal bottleneck resource with the least throughput performance in a production system. Because the pace of a system is determined by the drum, a detailed master schedule is determined based on the finite capacity of the drum (Betterton and Cox, 2009). A job is only released into the system based on the progress made by the drum, which explicitly controls the WIP within the system, forming a rope to create a pull system (Hopp and Spearman, 2004). The buffer is strategically positioned in front of the drum to prevent starvation.

In DBR, as all other elements in the system must be subordinated to the internal constraint resource, the detailed schedule generated is based on the finite capacity of the internal constraint resource; thus the system is less flexible in responding to market demand, particularly urgent orders. This causes customer orders with potentially higher long-term benefits to be rejected in the pre-sales stage.

From a business strategy perspective, Schragenheim and Dettmer (2000:157) argued that external market demand ultimately limits and determines the system's performance. Looking at a longer time horizon, internally constrained resources are temporary and can be elevated through innovative interventions or capital investment. Ultimately, the market dictates the system's throughput. In a system environment in which the ability to provide safe and reliable due dates is critical, market demand naturally becomes the drum that dictates the pace of the system. This perspective is not new and can also be seen in Kanban based systems such as Lean and CONWIP (see Hopp and Spearman, 2004).

S-DBR adopts a similar view, in which the market (customer) is the drum that drives the pull. The (potential) internal resource constraint is known as the capacity constraint resources (CCR) (Figure 1), with a time buffer used to protect the promised due date to the customer (drum). According to the TOCICO dictionary, this time buffer is known as the production buffer (PB) which is "a liberal estimate of time it takes from order release until completion (under regular load)" (Cox III et al., 2012). PB determination is highly dependent on the contextual environment. As it is desirable for most production to complete in the middle section of a normal distribution curve, this can be used as a rule of thumb to determine a practical PB. For an environment in which the touch time at CCR is significantly smaller than the queue time in the production process, industry practitioners suggest starting with PB taken as half of the existing total production lead time (Schragenheim, 2013). Further details on the assumptions and mechanism of S-DBR can be found in Schragenheim and Dettmer (2000), Schragenheim (2010), Lee et al. (2010), and Gupta and Boyd (2008).

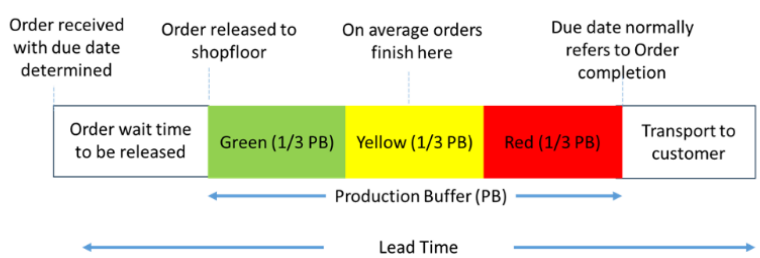

Figure 1. Production Buffer (PB) (Adapted from Schragenheim 2013:222)

2.3 Human empowerment

In the 70 – 80s, OPT used its algorithm and simulation capability to generate an optimized schedule was known as the new technology. The acknowledgement of OPT in the American Production and Inventory Control Society (APICS) attracted manufacturing companies from the FORTUNE 500, including General Electric and Ford, to implement it (Bylinski, 1983; Goldratt, 1980, 1981). However, Goldratt (1988) understood that the "superiority stemmed not from the algorithm, but mainly from these underlying concepts". The importance of understanding was also stressed by Hopp's recent review on the mixed results reported in Lean implementation where he warned against the "overreliance on tools, without a deeper understanding of lean thinking" (2018).

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The success of these implementations was highly dependent on the shop floor personnel's understanding of the system. This involved providing relevant data inputs and making sense of the schedule to support decision making in both the planning and execution stages (Goldratt, 1988). Efforts to challenge established thinking included the nine OPT rules (Goldratt and Fox, 1986) and the subsequent emergence of the five focusing steps (Goldratt and Fox 1986) Schragenheim 2010:211).

In PPC, it is useful to distinguish between the planning and execution stages and the associated decision making in each stage. The planning stage starts from the pre-sales stage which involves order acceptance, re-negotiation, or rejection-related decisions. The challenge in planning stage is to determine a reliable order due date (ODD) to support decision making. In the execution stage, decision making largely centers around fulfilling the promised ODD given to customers in the planning stage (Schragenheim, 2010:213; Wiendahl et al. 2005). The challenge in this stage is to determine the order priority (OP) based on both the promised ODD and the dynamic availability of resources.

DBR, particularly S-DBR was designed to address higher levels of variability and demand uncertainty than flow management associated with TPS use of Kanban. Environments with higher levels of variability and uncertainty (e.g. make-to-order (MTO) or engineer-to-order (ETO)) made it more challenging for shopfloor personnel to arrive at a practical decision around ODD and OP (Romero-Silva et al., 2022). To engage and support shopfloor personnel in making these decisions, two tools were introduced in TOC: planned load (PL) and buffer management (BM).

2.4 Planned Load (PL)

PL is the "accumulation of the derived load on the capacity constraint resources (CCR), or any other relatively highly loaded resource, of all the firm orders (released and awaiting release) that have to be delivered within a certain horizon of time" (Schragenheim, 2010:222). As shown in Figure 2, the total load includes the following: (i) workorders currently working on by the CCR; (ii) workorders released into the production system, and (iii) workorders waiting to be released into the production system (Schragenheim, 2010:180).

Under the general assumption that the position of the CCR is around the middle of the production system, a reliable ODD is determined by adding half of the PB to the current accumulated point of load on the CCR, whereas the order release date is determined by subtracting half of the PB from the current accumulated point of load on the CCR (see Figure 2). With the assumption that the touch time at CCR is moderately significant compared to the lead time, most of the materials will arrive at CCR in half of the PB time and complete the remaining processes in half of the PB time. Some proposed adaptation have been explored according to the contextual production environment. For example, the considerations related to the various position of CCR within a production system had been explored by Lee et al. (2010) by multiplying a ratio to the PB; and the multiple CCRs monitoring suggested by Schragenheim (2009:65) to address concerns related to wandering CCR.

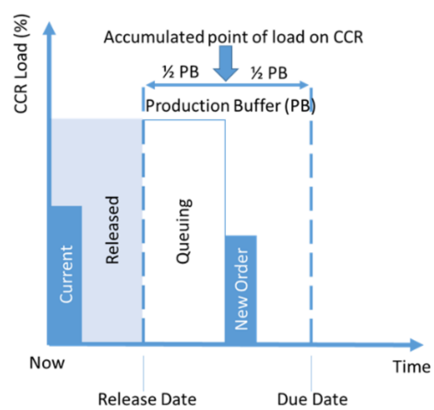

Figure 2. Planned Load and Production Buffer

2.5 Buffer Management (BM)

BM is a time-based pull control and signaling mechanism with the following four main functions (Cox III et al., 2012): (i) To prioritize tasks/orders based on buffer penetration/consumption. (ii) To expedite tasks/orders that are at risk of missing promised due date. (iii) To feedback any necessary buffer design parameters or escalate if it requires decision making by higher management (Stratton and Knight, 2010). (iv) To target areas for ongoing improvement activities (Stratton and Knight, 2010).

The implementation of BM in general TOC applications had been well-described by Schragenheim and Ronen (1990, 1991) and Simatupang (2000). In S-DBR, the PB is set into three 'buffer regions' each occupying one-third of the PB. Each region is represented by 'Red', 'Yellow', and 'Green'. These 'buffer regions' help shopfloor personnel to determine order priority and any need for proactive actions to manage the system's flow. Each order has a buffer status (BS) which is determined based on the progress of the order in relation to the BM. Once an order is confirmed, a BS is assigned to it based on the ODD. The BS is the percentage of buffer consumed in relation to the total buffer. The buffer consumed can be determined by subtracting the remaining time (from now until the ODD) from the buffer time. Decision making supported by PL and BM.

The combined use of PL and BM helps shop floor personnel to proactively manage the flow in both PPC stages. In the planning stage, the ODD determined based on the loading information made available through the PL can be used to assist decisions on whether to accept, renegotiate, or reject an order. Using the standard quoted lead time in the industry as a reference, an order can be accepted if the ODD is smaller and can be renegotiated or rejected as it falls beyond. In the event that it is a high-value customer with strategic importance to the business, PL can be used to help managers visualize the impact of various interventions before taking the most appropriate action, such as an increase in resource capacity over time or additional shift, renegotiating ODD for other customers, etc.

In the execution stage, the BS of each workorder can be used to assist day-to-day decisions regarding workorder prioritization. Figure 3 shows a list of work orders (1, 2, 3 and 4) with the production buffer (PB), planned release date, promised order due date (ODD), and the corresponding buffer status (BS). If the BS of a workorder is in the green region (0-33%), it signals that the order can be released into the system; the yellow region (34 – 67%) signals that an order should have been released into the system, and the red region (68 – 100%) alerts the need to expedite the progress which includes immediate release or escalation to higher management for necessary intervention. Workorders with a BS above 100% are late and can be assigned a black color code. Those smaller than 0%, awaiting release can be coded in blue. Apart from realizing pull, the inquiry process can be set up to identify the reasons for workorders entering the red or black regions. This can be used as a proactive diagnostic tool to signal the health status of a production system and inform necessary intervention for continuous improvement (Schragenheim and Ronen, 1991; Blackstone, 2010:161).

The use of a BM allows work orders at risk of being late to be flagged up. As illustrated in Figure 4, work orders without a BM would not react because the ODD is a distance away. The impact of local delays on the system level was masked, causing a reactive response to variation and uncertainties in the system. This signaling mechanism directly empowers shop floor personnel to take proactive intervention actions on work orders at the risk of late delivery.

Today: Day 8

Work Order (WO)	Production Buffer (PB) Time	Planned Release Date	Promised Due Date	Remaining Days	Buffer Status (%)	Colour
WO 3	11 Days	Day 1	Day 11	3	85	Red
WO 4	15 Days	Day 1	Day 15	7	53	Yellow
WO 1	5 Days	Day 1	Day 5	3	40	Yellow
WO 2	10 Days	Day 1	Day 10	8	20	Green

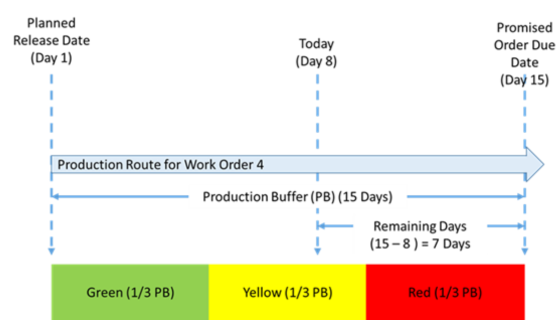

Figure 3. Buffer Status of Work Order 4

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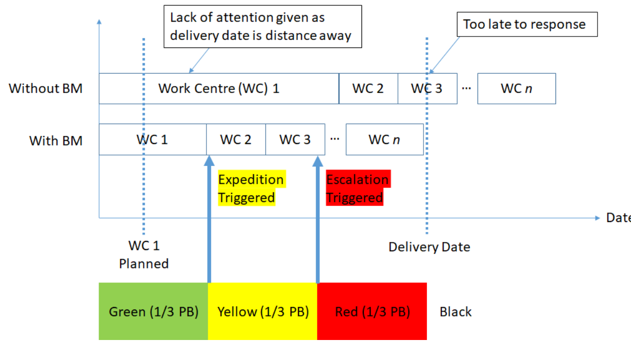

Figure 4. An illustration of PPC with and without BM

3. Methods and Data Collection

Driven by the objective to understand how the key perspectives in TOC on PPC are realized through S-DBR and its tools in a real-life context, case study was chosen (Yin, 2003). This methodology has been widely used in the field of operations management, which is practical by nature, to capture practical knowledge (Eisenhardt, 1989; Chris et al., 2002). The chosen case study was a two-year project where an associate was recruited and based full-time in the case company to lead and implement S-DBR based intervention from within the company. To the best of our knowledge, this is the first paper where the researcher was also the implementer.

This intervention project was divided into four broad phases: (i) Why change? (ii) What to change to? (iii) How to change? (iv) Sustain the change. Data was collected throughout the project via formal and informal meetings/discussions/interviews, job shadowing, observation of actual practice, direct communication with people, and company archival data (Bendoly et al., 2010; Crawford, 2001; McKay, 2001). The generic S-DBR strategy and tactic (S&T) tree used by both practitioners (Harmony, 2017) and researchers (Bernavides and Van Landeghem, 2015; Chakravorty and Hales, 2016) was used to guide the implementation.

4. The Case Company

4.1 Introduction

This case company was a small MTO roto-molding manufacturer that designs, produces, and markets its own range of plastic planters and bins, targeting the high-end market. It also offered molding services to a small group of customers. Apart from its unique and patented self-watering design feature in planters, it distinguished itself by providing customization services, such as color, mold-in graphics, crests, and plaques, without the requirement of minimum order quantity. The demand for planters was seasonal with peaks in spring and summer; whereas bins were by nature not a seasonal product but was ‘shaped’ to peak in autumn and winter, to keep the factory busy throughout the year. The typical distribution of order quantity over a year was heavily skewed towards a small order quantity, with more than 80% below 20 units, and 5% above 50 units. Despite this, all orders were quoted with the standard industry accepted lead time. It had been a tradition to utilize additional shifts in the summer to fulfil the demand (Figure 5).

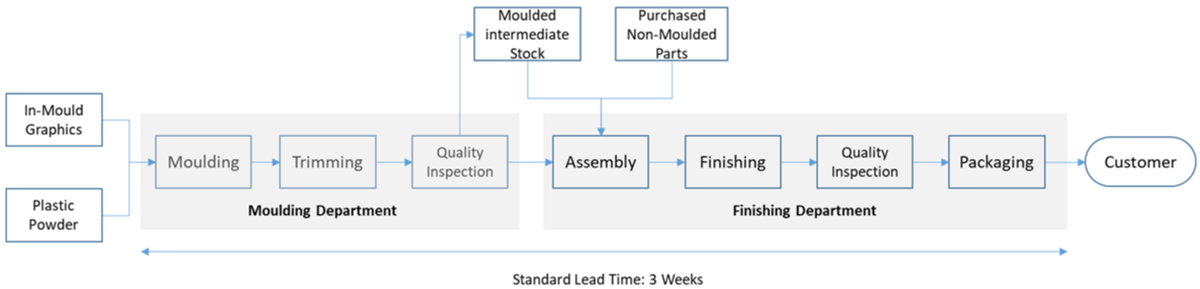

Figure 5. Production process in case company

The case company aspired to grow but struggled to keep up with existing demand. The reactive production system entailed senior management in day-to-day firefighting related activities, depriving the attention needed for business growth related activities. Past intervention attempts, including the introduction of bespoke manufacturing systems, had failed to achieve the desired growth. This was mainly because of the inherent contextual complexities of the company.

4.2 The Contextual Challenges

The production process was manual, labor intensive, and heavily dependent on practical knowledge and skills. While there were no dedicated production lines or resources, there was a dominant production process: molding, trimming, assembly, finishing, and packaging. Of these processes, molding required the longest touch time.

Rotary molding machines (R_i, where i is the machine) were key resources in the molding process. Over the years, the company has acquired different rotary molding machines. Each machine had two or three biaxial rotation arms on which molds could be mounted, which were known as mold spaces (R_{ijk}, where i is the machine, j is the arm number, and k is the mount space number). Different mounting frames were used to increase the total number of molds mounted per cycle. However, this was limited by factors such as the working load of the individual arm, the required vertical and rotational weight balance to achieve a constant rotation speed, the mold dimension, and the different working space clearance requirements of each mold. Apart from the availability of mold spaces, the availability of mold resources directly impacted the production throughput and capacity. Some molds were shared by different products, making it challenging to manually monitor their availability.

This was further complicated by the heating and cooling time requirement of each product, which was dependent on the mold design, quantity, and type of plastic powder used. Over-heating causes brittleness, which reduced the product's impact strength, whereas under-heating causes bubbles to form on the product surfaces because of the half-molten plastic powder. The combination of these factors presents a classic multiple parallel routing option problem in

PPC, making it challenging to determine the optimal process time, capacity, and throughput for production planning and execution (Figure 6).

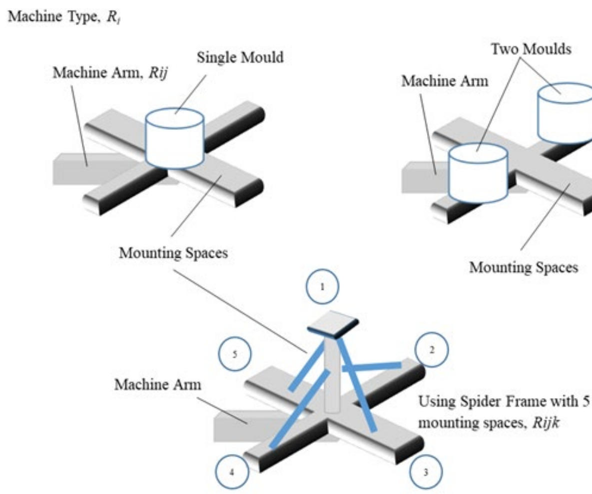

Figure 6. Molding resource consideration

5. Results and Discussion

5.1 S-DBR Implementation

The S-DBR-based PPC software was developed and implemented for the case company. This was integrated with the existing Sage system and used as a decision support system. One year after implementation, the company achieved the highest turnover in five years, 16% increase from the previous year, with only a total cost increase of 1.6%. The due date performance was over 90% with improved quality (lower scrap). This was achieved despite the company operating a single shift throughout the year for the first time. This shows that hidden capacity was exposed, with buffer capacity and time being more strategically deployed and used. Apart from achieving improvement in operation-related performance, shop floor personnel were empowered with decision-making and accountability. '*Management time is no longer spent on day-to-day production. Management now is very 'light touch' and only gets involved in issues beyond the responsibility of the team. There is more time to engage positively with the team rather than having to manage them on a day-to-day basis…*'

The implementation follows the five S-DBR implementation elements in the generic S-DBR strategy and tactic (S&T) tree used by both practitioners (Harmony, 2017) and researchers (Bernavides and Van Landeghem, 2015; Chakravorty and Hales, 2016). However, adaptation to S-DBR was required to suit the company's contextual manufacturing environment.

5.2 Buffer Management adapted

A potential approach to dealing with significant touch time and CCR location can be found in the existing literature (Lee et al., 2010; Scheinkopf et al., 2012; Schragenheim et al., 2009). However, both are discussed separately in conceptual and simulation-based articles. The issue of CCR location has been discussed, but with the assumption of an insignificant touch time (Schragenheim et al., 2009; Lee et al., 2010). The linear high touch time solutions proposed by both Scheinkopf et al. (2012) and Inherent Simplicity (2010) suggest the need to redesign the time buffer and implement frequent work order progress updates.

Aggregated buffer vs individual buffers

The case company used two standard lead time: three weeks for planters and four weeks for bins. Taking planters as example, two weeks were assigned to the molding department and one week to the finishing/assembly department, with embedded buffer time. The contextual production complexities highlighted in the previous section caused such buffers to be assigned disproportionately at the product level. Embedded time buffers were often wasted because of phenomena such as student syndrome, sandbagging, and Parkinson's law (Budd and Cerveny, 2010:47; Maylor and Turner, 2022:184).

As there was no standard touch time for all products, the allocation of specific time for department (two weeks for molding and one week for finishing) encouraged undesired behavior. With a set milestone, there was a tendency for job tickets, particularly the less favorable ones, to be left until the last minute (student syndrome). When the shopfloor was less busy, work naturally spread to occupy the entire allocated production time (Parkinson's law). Due to the lack of incentives to complete job tickets earlier than the set milestone, job tickets completed ahead of time (e.g. owing to less processing time required) tended not to be reported (sandbagging), causing time gained or unused buffer time to be wasted. Wasted buffer time puts job tickets at the risk of late delivery when Murphy strikes.

To reduce such undesired phenomenon, individual time buffers in departments were aggregated to protect the ultimate system constraint: market. This aggregated buffer was placed at the end of the production process before shipping (as illustrated in Figure 7). Statistically, it is argued that variability pooling can be buffered more efficiently through an aggregated buffer (Hopp and Spearman, 2021; 2008:313; Maylor, 2022:171-186; Realization, 2010:82-83). Practically, this allows a paradigm shift from local optima (and the associated behavior and practices) to system related performance (such as throughput) (Goldratt, 2009). Instead of hoarding over and waste time buffers in individual departments, aggregated time buffers can be shared and utilized when required.

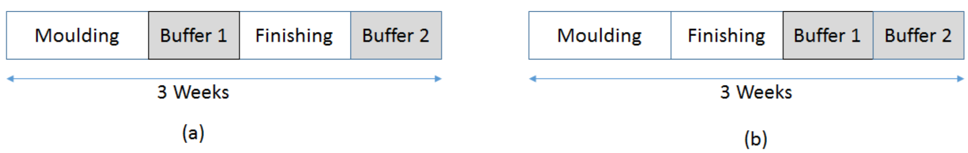

Figure 7. (a) Before: Distributed/Individual Buffer; (b) After: Aggregated Buffer

'Pooling'
It was observed that the production manager tended to group and produce products with similar mold in batches. This was because most orders were small in quantity, and the relatively laborious tasks involved with changeover. To better assist the production manager in making such considerations, the practice of 'pooling' was explicitly built into the buffer management, as shown in Figure 8. This was done by postponing the release of job tickets and placed them in the pooling zone. This also offered protection against uncertainties, such as order change or cancellation. It also reduced the work-in-progress (WIP) on the shop floor, allowing the production system to be more responsive to job tickets with higher priorities. As there were no existing rules to guide the number of pooling days, for convenience of calculation, a pooling time of six days was trialed using 'blue' as the color code. The remaining days were divided into the conventional three equal-sized colored zones of three days each (refer to Figure 8b). This buffer size could be further refined if required.

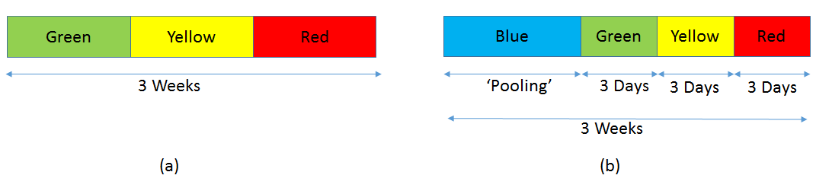

Figure 8. (a) Conventional BM; (b) New BM for Case Company

5.3 Planned Load adapted

The case company has identified molding machines as CCR. However, due to the complexities around molding resource allocation (as shown in Figure 6), it was overly generic if PL only monitors the molding capacity at the machine or arm level. Instead, PL monitoring was proposed at the frame mount position level. The mounting frames were reclassified into standard and special. Capacity of standard frames (preferred or most often used frames) on each arm were identified and used to monitor workload. Based on experience and tacit knowledge, shopfloor personnel were empowered to make decisions to introduce special frames as intervention. In certain instances, the mold might become a CCR, where its availability had direct impact on the production throughput. Instead of monitoring the

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detailed workload on the mold, only the next availability was monitored and updated. In resource allocation, this information was used together with the machine space availability.

The use of PL allowed the workload on capacity constraint resources (CCRs) to be monitored. We implemented two types of workloads: In-progress (orders currently on the machine) and In-queue (other confirmed orders). All confirmed orders received were given In-queue status and assigned to appropriate CCRs through the heuristic algorithm developed (not the focus of this paper). Shopfloor personnel were empowered to update the order status (from In-queue to In-progress or vice versa) and order progress (number of units completed). Shop floor personnel were encouraged to update after every production cycle (typically an hour) to allow the actual availability of resources to be swiftly reflected in the decision support system.

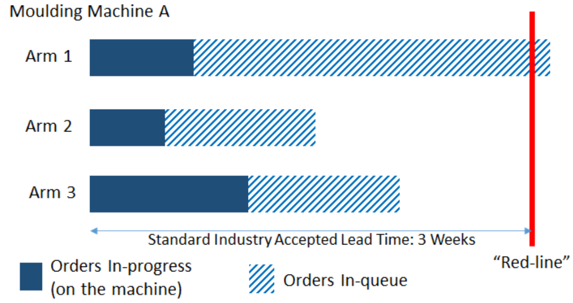

Figure 9. Planned Load with 'Red Line'

The 'Red Line' function (refer to Figure 9) proposed by Schragenheim and Dettmer (2010) was implemented by using the standard lead time offered to customers (three weeks from 'today'). This forward-looking visual representation provided early alerts which helped to manage the potential CCRs proactively. For example, the decisions related to activation/deactivation of buffer capacity (through altering machine-mold configuration, over-time, or additional shifts) or buffer time (by increasing delivery date).

5.4 ODD and OP related decision making

In the pre-sales stage, the planned load (PL) and buffer management (BM) tools were used to offer, accept, negotiate a feasible delivery date with customers or reject an order. First, a provisional delivery date, DD_p, was determined by adding the total touch time, T, to the first available time slot, $t_{available}$, of the potential CCR. The touch time, T consisted of the molding department, t_m and finishing department, t_f. The requirement of a machine-mold match was explicitly considered in the planning stage by using the latest available time slot between the machine and mold as the first available time slot of the potential CCR (as illustrated in Figure 10, where t_2 was used as $t_{available}$).

Equation (1):
$$\boldsymbol{T = t_{\mathrm{m}} + t_{\mathrm{f}}}$$

Equation (2):
$$\boldsymbol{DD_P = T + t_{\mathrm{available}}}$$

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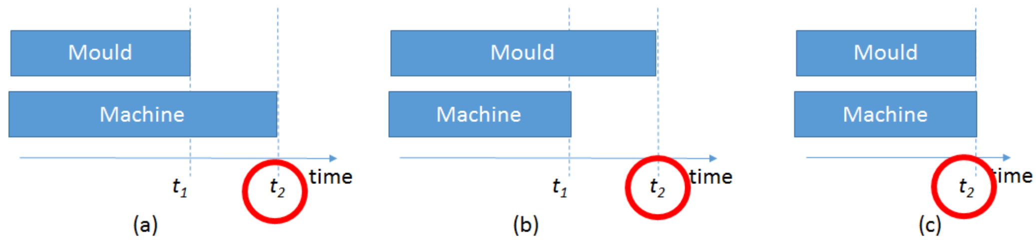

Figure 10. Illustration of First Available Time Slots of Mold and Machine

Next, the reliability of the provisional due date, *DDp* is checked using the time buffer redesigned in the previous section. This is done by calculating the buffer penetration, *BP* (as a percentage), using Equation (3).
Equation (3):

$$\%BP = \frac{DD_p}{DD_s} \times 100\%$$

where DD_s is the standard due date computed by adding 3 weeks (standard lead time of 15 working days) from 'today', as shown in Equation (4) and illustrated in Figure 11.

Equation (4):

$$DD_s = t_{available} + 15$$

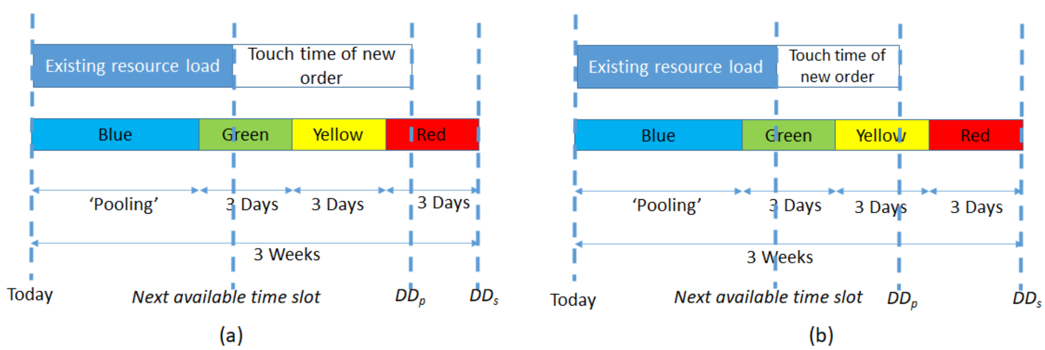

Figure 11. Due Date (a) red zone %BP; (b) yellow zone %BP

As customers are familiar with the existing standard industrial-accepted lead time of three weeks (or 15 working days) offered by the case company, it is desirable for the case company to maintain similar commitment. However, this is not at the expense of the case company's reliability in fulfilling its promised delivery date. A reference is proposed where job orders with DD_p in the yellow zone or earlier use DD_s as the promised delivery date. For job orders with DD_p in the red zone or later, an additional time buffer of five working days was added to the DD_p. This is expressed by Equation (5).

Equation (5):

$$ODD = \begin{cases} DD_s, \; if\ \%BP \leq 80\% \;\; (\text{yellow zone and below}) \\ DD_p + 5 \;\; if\ \%BP > 80\% \; (\text{red zone and above}) \end{cases}$$

While there is no specific guide on the number of days to be added, the generic S&T for S-DBR recommends having a single buffer unless there is significant lead time between products. Assuming that the consumption of time buffer is a normal distribution, where most of the orders completion falls in the yellow zone, the addition of five days places the delivery date in the mid-green and mid-yellow zone. Given that more than eight percent of the orders are in small quantities, this provides an adequate time buffer. For large orders, this provides early alerts with relatively large remaining lead time for management interventions.

In the execution stage, the %BP of all accepted orders is refreshed periodically, triggered by a set timer (5 min) or whenever there is a new input into the system. A company-wide priority system was established by adopting %BP as the BS of orders, together with its color zones, realizing a pull mechanism.

5.5 Consideration of assembly products

There were assembled products in the case company that required multiple molded components. For example, one of the best-selling products required up to 15 different molded components. Each molded component had varied machine/mold requirements, hence different touch times. If the individual molded components were planned in the same way as the non-assembled products, it might cause molded components to complete at different times, resulting in missing components during assembly. As illustrated in Figure 12, owing to the different production requirements, components A, B, and C had different buffer statuses and order priorities. Consequently, components A and B were not ready at time, t_f.

In traditional Drum-Buffer-Rope practice, a separate time buffer, known as the assembly buffer, was used to ensure 'full kit' status, ready for assembly. However, to avoid confusion and complexity, S-DBR prefers the use of a single time buffer sized buffer management for both the planning stage (such as delivery date determination mechanism) and execution stage.

To achieve this, all molded components of a product assembly were treated as individually molded products. Instead of having an individual touch time for the finishing stage, the longest finishing touch time among these components was determined and used to calculate each component's total touch time. This allowed all molded components for an assembly product to share a common priority system. The delivery date for the assembled product was determined by using similar mechanisms for non-assembled products. However, the touch time of the molded part with the longest processing time was used. This delivery date was shared by all molded parts within the assembly product.

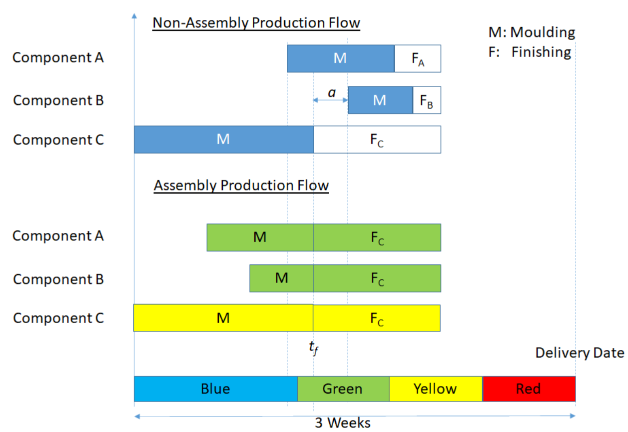

Figure 12. Consideration of Assembly Product

Referring to Figure 12, Component C had the longest post molding processing time, F_C. This was added to the processing time for both Components A and B replacing the original F_A and F_B. This automatically aligned the order release priority according to the 'full kit' requirement. Instead of having a separate buffer, it was anticipated that the aggregated buffer was adequate to provide the necessary feedback signal to manage the priority of all molded parts.

6. Conclusion

To the best of our knowledge, this is the first reported S-DBR study where the researcher was also an active change agent from within the case company. This offered an opportunity to understand and capture the adaptation needed to implement S-DBR. This intervention has successfully improved the operation performance of the case company and empowered sales and shop floor personnel in making day-to-day operations related decision-making, such as ODD and OP.

6.1 Flow management and human engagement

The S-DBR approach to consider the market as the ultimate system constraint explicitly places the focus of business operations on meeting market demand. From the perspective of PPC, this means to quote a reliable ODD to customers in the planning stage and fulfil them in the execution stage, a key challenge for MTO companies. This explicitly views business operations, from order quotation to order fulfilment, as a system. Actions and decision-making in both the planning and execution stages should not be done in isolation. Instead, it is a dynamic feedback system in which the ODD is determined based on the execution progress made on the shopfloor, effectively controls both the input flow and the WIP. In the execution stage, the flow is managed using the proposed ODD to generate a system-wide priority system. This is realized through two tools in S-DBR: Planned Load (PL) and Buffer Management (BM).

Using a case study implementation, this paper demonstrated how flow management can be realized using both PL and BM, enabling proactive production planning and execution. Scenario planning can be performed in the order quotation stage using both PL and BM to determine whether an order should be accepted, renegotiated, or rejected. For valuable orders or urgent orders from preferred customers, further discussion can be conducted between sales and production departments to identify potential bottlenecks and explore intervention options to strategically accept such orders. Intervention options include deployment of additional capacity resources or renegotiating ODD with other customers.

In the execution stage, PL together with the 'Red Line' enables visibility of resource loading into the near future. This allows CCRs to be proactively managed, where the buffer capacity can be strategically and proactively deployed. Through scenario planning, the impact of additional resource capacity deployment (such as additional work shifts and investment in new resources) or reduced resource capacity (such as absence due to illness, annual leave, and scheduled maintenance) can be simulated and proactively managed.

It is not the purpose of S-DBR to generate a detailed schedule in which the job sequence on the shop floor is strictly adhered to. Rather, the BM signaling mechanism provides early warning and flexibility, which empowers personnel to take proactive initiatives to resolve potential issues. The data provided by PL and BM facilitate communication on the shop floor, inter-department, customers, and the wider supply chain. Adherence to the BM promotes system-based performance and minimizes local optima.

Given that the production process in this case company is labor intensive, apart from the S-DBR concepts and tools, the practicality of the deployed decision support system depends heavily on shop floor personnel maintaining a reasonable updated work order progress if not in real time. Simple and user-friendly progress update interfaces have been developed to encourage timely update.

As demonstrated in this case study, adaptation to suit contextual manufacturing is necessary, and multiple continuous improvement iterations are required for the decision support system to stabilize. The key to realizing this requires the active participation of change agents within the company and the willingness to share production-related tacit knowledge. This allowed new practical knowledge to be generated, captured, and used to inform the redesign of time buffer and planned load.

The adeptness of shop floor personnel in 'interacting' with the decision support system appears to be a common theme that emerged from the above discussion. Apart from contextual knowledge, it is crucial for users of the decision support system from all levels to understand and appreciate the underlying assumptions used in developing the system. Given that the business environment is both contextual and dynamic, such appreciation will help establish a culture of collaborative problem-solving and continuous improvement. This can be further extended to be reflected in the organization's talent management related recruitment, development, appraisal, and reward policies.

6.2 Future research

Given that the concept of CCR and PL have similarities to the more popular workload control (WLC) PPC mechanism, crossbreed analysis between WLC and S-DBR can potentially be explored through practical implementation (Fernandes et al., 2014; Thurer et al., 2017). Although there are various existing comparison studies between WLC and other PPCs, they are largely conceptual and simulation-based (Romero-Silva et al., 2015). For example, BM from

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S-DBR can be explored as an overarching mechanism in WLC for order release decision making and priority dispatching.

Human factors have been highlighted in this research as a critical element in PPC and should be explicitly embedded in the development and design of PPC into a decision support system. In this era, where digital technologies such as artificial intelligence (AI) have proliferated, it is important to establish a healthy human-AI relationship in the context of PPC. This area can be further researched to explore how the concepts and tools in S-DBR can potentially be used to resolve the tension between automation and augmentation in PPC.

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