Design and implementation of a Drum-Buffer-Rope pull-system

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Purpose: This paper investigates the selection, design and implementation of a Drum-Buffer-Rope (DBR) type of production pull-system in a panel fabrication plant characterised by extensive shared, batch resource resources within a low volume UK manufacturer of large vehicles. This was the second of a series of two related research projects conducted under the aegis of a Lean initiative at this case firm.

Design/methodology/approach: A purposively selected longitudinal case study conducted over 24 months and organised around a two phase research design. The initial body of evidence included a detailed map constructed by a project team of eight managers and accountants during a two day structured workshop; numerous unstructured interviews and observation of shop floor practices; document and archival analysis, and 140 photographs of the focal operation. Supplemented by extensive financial and operational data extracted from the firm's accounting and MRP systems, including all data necessary to construct and implement bespoke capacity planning, work in progress (WIP) monitoring and simulation modelling tools. The case firm is anonymised.

Findings: The Lean manufacturing literature ignores the real-world issue of shared resources, and this gap is attributable to the concept of 'rightsizing' tools and equipment that is widely promoted within the Lean community. The case panel plant is characterised by extensive shared resources; many of which are also batch processes. The most appropriate pull-system method for this production environment is DBR. The detailed design of the DBR mechanism required a controlled transfer buffer of overhead conveyance capacity after the Drum because the extent of downstream process variability risked it being unable to offload panels, hence compromising throughput.

Research limitations/implications: The study is based upon a single case. This consequently has implications for the ability to generalise from the results.

Practical Implications: When the DBR pull-system design was implemented it reduced the number of panels in WIP by 60%. This equated to a 56% (18 days worth) reduction of manufacturing lead time and more than doubled the plant's inventory turns (from 9.1 to 21.2). It also significantly improved delivery schedule adherence, with downstream jig stoppages in the Final Assembly falling from an average of six to less than one per week. The financial benefit was independently audited to equate to an annualised value of $850 K. Consequently, this project was awarded the first prize at its parent enterprise's annual worldwide process improvement competition.

Originality/value: This paper details a novel technique that permits the routings of multiple value streams to be mapped and is useful for highlighting the identity and location of shared resources. It also contributes significantly to the literature that is available on the relationship between the Lean paradigm and the management of shared production resources, and adds to the literature on the detailed design and implementation of a DBR pull-system in a jobbing-type of environment.

Keywords: pull-system; Drum-Buffer-Rope (DBR); shared resources; lean; theory of constraints (TOC)

1. Introduction & background

This paper investigates the design and implementation of a Drum-Buffer-Rope (DBR) type of production pull-system (after Goldratt and Cox 1984) in a panel fabrication plant at a low volume UK manufacturer of large vehicles. This two-year longitudinal case study was conducted under the aegis of a Lean manufacturing process improvement initiative (Womack, Jones, and Roos 1990; Womack and Jones 1996). This case is the second in a series of two related studies that were conducted by the researchers at the firm, which is referred to as VehicleCo for the remainder of this paper. The previous study established that, rather than focus on [labour] cost reduction, the most logical course of action for the firm to increase its profitability was for it to increase its throughput. It also established that to achieve this necessitated the reduction of manufacturing lead time (MLT) via the reduction and subsequent control of work in progress (WIP). It also determined that the consequent intervention project should take the guise of the implementation of a production pull-system, and that this intervention should be made within VehicleCo's bodywork and auxiliary product panel fabrication plant; a jobbing environment that was characterised by extensive shared resources (machines and assets that were not dedicated to any single downstream product line/contract).

Even though the subject of Lean manufacturing can boast a lineage of over three decades (Schonberger 2007) and continues to be the subject of extensive publication, it suffers from a problem of interpretive viability; lacking common definition and meaning different things to different people (New 2007; Shah and Ward 2007; Bayou and De Korvin 2008). As an aid to overcoming this dilemma, a common feature of many publications on the subject of Lean over the last decade and a half has been the citation of Womack and Jones' (1996) wellrehearsed 'Five Lean Principles' as a generic prescription for achieving Leanness, and this provides a useful framework for considering the salient literature that underpin this study. Their first principle holds that the starting point for becoming Lean is to specify 'value' from the perspective of the end customer, and usually in terms of a specific product or product family. Principle two is to then identify the 'value stream', which the authors define as the sequence of common processing steps, equipment or activities required to produce and deliver that product or product family to the end customer. Once the value stream has been mapped and the obviously wasteful steps eliminated, the third principle is to make the remaining (value-creating) activity steps 'flow' without delay or obstruction in order to achieve a significantly reduced MLT. This involves eliminating or minimising work queues, rework, backflows and all other types of stoppage. Having enhanced responsiveness in this manner, the fourth principle is 'pull'. This means producing only in response to a specific customer demand signal rather than making-to-forecast. The fifth and final principle is 'perfection'. This embodies the concept of kaizen (Imai 1986) and entails continuously improving the production process to produce exactly what the customer wants, exactly when they need it, with zero defects, at a price the customer is prepared to pay and with minimum waste.

When the large and expanding literature on the subject of Lean is reviewed to provide guidance on the proposed pull-system implementation within the case fabrication environment, it reveals a surprising lack of coverage on the subject of Lean implementation within jobbing environments; particularly with regard to the relationship between Lean and shared resources. Only Duggan (2002) seems to recognise the existence of such shared resources. He acknowledges that shared resources, along with high product mix and information flows, are the three key practical impediments to implementing flow and pull in real-life factories. However, his 'Mixed Model' value stream mapping (VSM) technique focuses on managing a high variety or mix of products variants through a single value stream and he too offers no advice on the management of shared resources. This literature gap appears to be attributable to a systemic issue, as the wider Lean community universally promotes the concept of 'rightsizing' tools and equipment as an important trait for achieving Leanness (e.g. Womack and Jones 1996, 2005; Stenzel 2007). The lean right size concept calls for the use of resources within production cells that minimise the impediments to product flow. This concept in turn has two constituent components. The first is the selection of a resource whose scale requirements do not drive batch and queue activity. Large-scale resources that drive batch and queue activity are known as 'monuments' to the Lean community, and these often drive behaviour that focuses on efficiency and utilisation rather than making only the quantity that meets actual customer demand. Its second component is the dedication of resources within a production cells to a specific product or product family 'value stream' in order minimise delays attributable to set-ups and changeovers. Due to the dedication of assets, the issue of resource sharing is therefore avoided.

Against the above background, the research problem was therefore to design, and successfully implement, an appropriate pull-system for the case company's jobbing environment. The successful achievement of the research objectives associated with this promised to contribute to the literature that is available on the relationship between the Lean paradigm and shared production resources, and also promised to yield commercial benefit to VehicleCo in reciprocation for the research access.

In order to relate this study to the wider dialogue and to detail the methods and techniques subsequently drawn upon, the paper starts by reviewing the key literature on production push and pull systems, along with the most influential and commonly implemented pull-system methods. This includes the DBR method proposed by Goldratt and Cox (1984) as part of their theory of constraints (TOC), which was subsequently selected as the basis for the implemented design. Next, the research context is elaborated upon in order to provide detailed insight into the case firm and the focal panel fabrication plant. This is followed by the research methodology that explains the research context, strategy, research design and data collection procedures that were developed to achieve the objectives identified above. The penultimate section is a discussion of the findings derived using this methodology, which is organised according to the two phases of the research design. The paper concludes with a summary of its academic and practical contributions and an indication of future avenues for research.

2. Literature

2.1. Push vs. pull-systems

Returning to the framework introduced in the previous section and it is possible to determine that Womack and Jones' (1996) third and fourth Lean principles of flow and pull are embodied in the concept of production pullsystems. Hopp and Spearman (1996) suggest that the origins of these widely used terms can be traced to their use in a general sense by Ohno (1988) in his explanation of the Toyota production system (TPS), and came into common currency in the early 1980s to explain and differentiate the JIT phenomenon from the conventional Western MRP-based approach to production planning and scheduling. In the interest of clarity, they offer the following definition of these two terms: A push system schedules the release of work based upon demand, while a pull system authorizes the release of work based on system status (Hopp and Spearman 1996, 317).

Whilst these authors state that these two terms are not precisely defined in the wider literature, reference to this reveals that the term push-system is often used as a synonym for MRP-based scheduling (see e.g. Gupta and Boyd 2011, 608; Hill and Hill 2012, 436) and will be used in this context for the remainder of this paper. Hopp and Spearman elaborate that in such an

MRP-based push-system a job is released to the factory floor in response to an exogenous schedule and the timing of the release is not influenced by wider happenings in the plant (such as machine downtime). Indeed, the design aim of such a push-system is to minimise the inventory carrying costs whilst simultaneously seeking to maximise the capacity and labour utilisation (Boyd and Gupta 2004, 359–60). By contrast, the design aim of a pull-system differs; this being to match the flow of work through the production process with the demand signal so as to maximise that process' responsiveness to end customer demand. Consequently, within a pull-system, a job is only released in response to an authorisation signal generated by some change in status to the production line. This is usually the completion of work at some point in the production process (Boyd and Gupta 2004) Therefore unlike the push-system, a pull-system will place an inherent limit on WIP and will hence prevent 'overproduction' (after Ohno 1988).

Although Hopp and Spearman (1996) recognise that multiple forms exist, they observe that the pull-system is often viewed as being synonymous with the kanban method (see e.g. Laugen et al. 2005) and attribute this observation to the nature and influence of the early publications on the TPS. For example, whilst Hall (1981) acknowledges that different types of pull-system are possible and he only describes the Toyota kanban approach in detail. Likewise, Schonberger (1982) only refers to pull-systems in the context of the TPS kanban approach.

Bicheno (2004) states that kanban is but one of three of the most influential and commonly implemented pullsystem methods within manufacturing; the other two being constant work in progress (CONWIP) and DBR.

These are each now considered in more detail.

2.2. Kanban

The Japanese word 'kanban' entered the management lexicon in the early 1980s and its literal translation is 'visible record' (Schonberger 1982, 86). This was the term adopted by Taiichi Ohno to name the method within his TPS for governing the flow of material through the plant (Hopp and Spearman 1996, 162), because within the TPS the signalling device took the form of a manually prepared card that acts as a visual trigger to order more parts (Schonberger 1982). Many different forms of kanban have subsequently been developed and Bicheno (2004) provides a useful summary of these. He distinguishes between production kanbans that authorise the production of a new batch of parts, and move (or withdrawal) kanbans that provide permission to release work to the shop floor or move of a batch of material between a pair of processes or resource centres. The TPS described by Ohno (1988) was based upon a dual card kanban approach that used both production and move kanbans. Within this approach, each individual card represents permission for the upstream supplying resource to produce and or move a pre-designated quantity of a specific part to a pre-designated downstream customer resource location. The number of kanbans in a given loop will therefore depend upon demand and, if demand changes, then the number of kanbans can be adjusted accordingly.

Kanban is commonly used in conjunction with the 'supermarket' technique (Rother and Shook 1998; Bicheno 2004). This is an inventory storage area that is located in physically close proximity to the supplying resource centre and contains one or more standard containers of every part produced by it. The supermarket works by the customer resource signalling the quantity of each part that it needs from this upstream supermarket by sending it a move kanban. When the move kanban is received, it results in the withdrawal of the requisite number of parts from the supermarket by the material handler, and the subsequent conveyance of these parts to the customer resource. The supermarket derives its name from the material handler 'shopping' for parts from a series of supermarket locations along a pre-designated and highly predictable route; which is often likened to a bus route. This withdrawal in turn stimulates the issuing of a production kanban from the supermarket to the supplying resource centre in order to replenish the parts withdrawn. In this way, final customer demand and the replenishment pull-signal is 'rippled' upstream.

In a Lean production system, such supermarkets are often used to coordinate the synchronisation of workflow governed by a 'pacemaker' resource, which is a scheduling concept that calls for production for the whole plant to be scheduled at this single point (Rother and Shook 1998; Bicheno 2004). Indeed, it is from the resultant production rhythm dictated by this scheduling point that the technique derives its name. Serrano, De Castro, and Goienetxea (2009, 294–295) establish that there is no precise formula for selecting the pacemaker resource. They suggest that in make-to-order manufacturing systems that operate with long takt times, it is recommended to use the first resource centre as the pacemaker. However, citing Rother and Shook (1998), they suggest that in T-shaped assembly to order (light assembly and automotive) plants of the type in which this technique originated, it is deemed good practice to select a resource near the customer, often in a final assembly cell. Bicheno (2004) points out that the pacemaker need not necessarily be a constraint or bottleneck resource, although it often is in practice. He concurs that it is usual to select a process 'well downstream' so that resources upstream of the pacemaker can be pulled using the supermarket technique, whilst those downstream adopt first in first out mechanisms to manage the workflow to the customer. To work effectively, the pacemaker concept demands high production flexibility (Serrano, De Castro, and Goienetxea 2009) and smooth demand (Bicheno 2004).

Whilst kanban and its associated techniques offer reduced response time and inventory levels compared to a traditional push-system (Boyd and Gupta 2004), its inherent limitations have been recognised by authors since the earliest publications on the topic. For example, Hall (1981) recognises that kanban is a method for repetitive manufacturing and will not work in a jobbing environment. Similarly, Schonberger (1982) highlights that Kanban is feasible in just about any plant that makes goods in whole (discrete) units … (226) but cautions that it is only beneficial when used as an element of an holistic JIT [Lean] system; the parts included in the kanban system should be used every day and that very expensive or large items should be excluded from kanban. Citing the work of Gianque and Sawaya (1992) and Jonsson and Mattsson (2006) argue that kanban is most effective in a production environment that is characterised by regular and steady demand, where products have a simple and flat bill of materials (BOM) and short lead times, and where there are small order quantities. Likewise, Bicheno (2004) warns that kanban requires a stable manufacturing environment where there is repetitive production (107).

2.3. CONWIP

The second pull-system discussed here is the CONWIP method advanced by Spearman, Woodruff, and Hopp (1990) who present it as being applicable to a wider variety of production environments than kanban, although they recognise that unlike DBR (next), it cannot be applied in a pure job shop environment (888). CONWIP is premised upon the principle that the simplest way to limit the amount of WIP in a production line is simply to enforce a protocol of not allowing the release of any more work to it if WIP is at, or above, predetermined limits (Hopp and Spearman 1996) and (Lee et al. 2011). It is from this method of achieving a constant level of WIP that this pull-system derives its name. Spearman, Woodruff, and Hopp (1990) point out that like kanban, CONWIP relies on a material release signalling device such as a card. However, unlike kanban, these cards do not operate between pairs of resource centres. Instead, the cards follow the product or batch through the complete circuit of all of the resources in the production process concerned. When the batch is finally completed on the last resource centre, the card is removed and returned to the first resource centre in the loop. Also, in contrast to kanban, CONWIP cards are not part-number specific. They merely authorise the release of the next batch of work, of whatever type is required, to this first resource in order to initiate its production. The actual part numbers scheduled to be produced next are matched to the card when work is needed for this first resource. Therefore this system facilitates explicit control over the sequencing of parts to be produced and is also amenable to re-sequencing by production control personnel when this is deemed appropriate. However, once a batch enters production, the queuing rule used at all resource centres is 'first in, first out'.

Compared to kanban, Spearman, Woodruff, and Hopp (1990) conclude that CONWIP requires lower WIP levels for the same level of throughput. This is because CONWIP does not maintain WIP for each part number [in supermarkets]. The authors also emphasise that CONWIP requires less strict operating conditions and linearity of flow compared to the kanban method. However, Bicheno (2004) highlights that kanban is the tighter material control method, and also facilitates the more rapid identification of production problems when production stages are well balanced. He stresses that the inherent strength of the CONWIP method resides in its conceptual simplicity and robustness to errors. This robustness extends to the identification of the bottleneck location, as within the CONWIP method, WIP automatically accumulates in front of the bottleneck (Spearman, Woodruff, and Hopp 1990). Bicheno (2004) therefore concludes that CONWIP is an attractive pull-system for operations that are characterised by maintenance problems, or a shifting product mix, that would cause the bottleneck location to change.

2.4. DBR

The third main pull-system is the DBR method proposed by Goldratt and Cox (1984) as part of their TOC. According to these authors, the goal of any (private-sector) organisation is to make money, and they introduce the concept of throughput accounting (TA) to guide managers to make decisions that attain this (Mehra, Inman, and Tuite 2005). TA is premised upon three measures that differ in definition to their more conventional usage (Corbett 1997): 'Throughput' is the rate at which the system generates money through sales. This is the volume of sales expressed in terms of money rather than units, and products only become throughput when they are actually sold. The second measure is 'inventory', which is defined as the money invested by the system in things that it intends to sell. Within TA this measure encompasses equipment and facilities in addition to the conventional inventory categories of raw material, WIP and finished goods. However, in the case of the latter categories, it equates to the direct material cost and excludes any notion of value added during the production process. The final TA measure is 'operating expense', which is defined as the money that the system spends to convert inventory into throughput. The TA conception of operating expense is notable for excluding all overhead allocations (Boyd and Gupta 2004). Goldratt and Cox (1984) argue that all management decisions should be based upon these three criteria alone, with the aim being to increase throughput whilst simultaneously decreasing inventory and operating expense. Such a decision is classified as 'productive' as it will contribute to the organisation achieving the goal.

Gupta and Boyd (2008) suggest that the TOC literature provides guidance for managing processes at three levels. At the first, highest level, TOC asserts that, in any complex system, only intervention at the system's constraint will have a significant and immediate impact on the whole system; whereby a constraint is defined as the resource with the highest capacity utilisation. Goldratt and Cox (1984) offer what they term the 'Five Focusing Steps' as a framework for the process of ongoing improvement to manage at this level. In summary, these steps are: (1) identify the constraint; (2) exploit the constraint's existing capacity; (3) subordinate the rest of the system to the constraint before acquiring additional capacity; (4) elevate the constraint by adding additional capacity; and (5) return to Step 1 if the constraint is broken.

Gupta and Boyd's (2008) second, operational level of TOC process management encompasses Goldratt's (1995) V-A-T classification of three basic plant configurations. This classification is derived from the BOM of the products produced within each of the respective configurations, and it provides useful insights into the common issues encountered within each, which Gupta and Boyd (2008) suggest revolve around misallocation of materials for V-plants and T-plants, and misallocation of resources for A-plants. V-plants contain relatively few raw materials that are converted into a wide variety of finished products; with some being sold off in part-completed states. This category includes steel mills and paint plants with typical business issues including low plant utilisation, poor due date performance and high operating expenses. A-plants contain a large number of components to make a small number of end part numbers, and are characteristic of the capital goods industries. Typical business issues include synchronisation challenges, labour utilisation, high WIP levels, long lead times, poor due date performance and large overtime costs due to expediting activity. The last category is the T-plant, which is characteristic of light assembly and the automotive industry. This category of plant contains a core of common components that are converted into a very high variety of end part numbers. The typical business issues here include the reliability of component supply and purchased part lead times, high component stocks and shortages.

DBR forms the third, detailed level of Gupta and Boyd's (2008) process management framework. In DBR, the 'Drum' is the most highly utilised resource that acts as the capacity constraint within a given production system, and hence dictates the entire throughput of that system. As per the pacemaker concept discussed earlier, it is from this pacing characteristic that the Drum derives its name. By definition, there is no catch-up capability if any production is lost on the Drum (Goldratt and Cox 1984). The 'Buffer' is WIP inventory that is located in front of the Drum and is designed to protect it against uncertainty by ensuring that it can keep working for a pre-designated period of time in the advent of failure of one of its upstream processes (Goldratt and Cox 1984). Consequently, the size of the Buffer is an important decision and should be a function of the probability of failure upstream of the Drum. The most distinct feature of the Buffer is that it is time-based rather than being determined as a discrete quantity of units in the manner of kanban. The third and final component of DBR is the 'Rope'. This is a long-distance signalling mechanism that connects the Drum to the gateway resource at the beginning of the production sequence. The Rope acts as a control mechanism for regulating the release of work into the system rate (Bicheno 2004). If for example the Drum processes an hour's worth of work, the Rope is used to communicate permission to the gateway resource to release the next scheduled hour's worth of work into the system. It is from this 'beat' of production that the Drum obtains its name. In this way, the amount of WIP and hence MLT through the process become predictable and the new work released becomes synchronised with the Drum processing rate. The Drum therefore acts as the single scheduling point in the system, with the processing sequence at the Drum being influenced by how fast the inventory processed can be turned into cash (Bicheno 2004).

3. Research context

The focal case firm is part of a large multinational enterprise that is headquartered outside of the UK. VehicleCo's UK operation designs, manufactures and supports a variety of structures for this parent enterprise's range of products. At the time of the study reported upon in this paper, this company had a portfolio of more than 20 separate products/size variants, which the firm terms 'contracts'. The panel structures for each contract are assembled on dedicated production lines in its final assembly area. Each panel set is unique to a contract. Also, each individual panel within each contract is unique. As a consequence, there are a relatively large number of unique parts and structures. On completion, these end products are shipped to another plant within the parent group for the integration of various systems and the kitting out of the vehicle interior.

The objective of the previous project conducted by the researchers at VehicleCo had been to develop a new and objective method for targeting a Lean (Womack, Jones, and Roos 1990; Womack and Jones 1996) process improvement intervention that promised to yield the largest financial impact within this large, geographically dispersed and complex manufacturing firm. Analysis of the project findings had clearly indicated that the most logical course of action for VehicleCo to increase its bottom line performance was for the firm to increase its throughput via a targeted WIP reduction intervention. A new targeting mechanism that came to be known as a Big Picture Financial Map was developed as part of that project and was used to identify which of the production work centres within VehicleCo's six UK plants offered the greatest financial potential for the initiative identified. This analysis indicated that the WIP reduction intervention should be made at the firm's bodywork and auxiliary panel fabrication plant named WC2-Panels (referred to as 'WC2' for the remainder of this paper).

WC2 is a 221,000 square foot plant that is located approximately one mile from the Final Assembly Hall (FAH) and houses 350 staff. WC2 acted as a key supplier to almost all of VehicleCo's final assembly production lines and was considered an operational 'problem child' at the time of the study as it was suffering from high WIP, long and unpredictable MLT (measured at the outset of the project to be an 'average' of 40 days) and high rework and scrap rates. It was consequently suffering from poor delivery schedule adherence, being late approximately 60% of the time, which in turn was causing an average of six jig stoppages per week within final assembly. WC2 was therefore causing much disruption to the production schedules of its downstream FAH customer, and this was clearly undesirable in an industry characterised by contractual penalty clauses for late delivery. To compound this existing problem, the firm's order book had recently witnessed a significant uplift as the firm's market recovered from a period of recession. When VehicleCo modelled the implications of this new order book they found that, within the immediate months ahead, they would be encountering a serious operational problem within WC2. In accord with conventional mass production practice, their traditional response to more demand had been to push more work into the system that would compound existing issues; producing more WIP that in turn would increase working capital and MLT, and also increase the risk of obsolescence and damages (but would not increase throughput). This dilemma was poised to become acute as apart from the cost, working capital and MLT implications, the modelling of the uplift in the order book established that if current working practices were followed there was physically not going to be enough space within WC2 to accommodate all of the panels that were forecast to be produced, stored and conveyed between its 68 constituent resource centres (each a distinct machine or group of co-located like machines).

The supply of panels from WC2 was decoupled from its downstream final assembly customer via a PreAssembly Buffer (PAB) storage area, and was scheduled using an MRP system (a characteristic push-system). It was within this context that the [second] applied research project at VehicleCo was launched, with the specific objective of designing and implementing an appropriate pull-system to control the flow of work through WC2 and hence the replenishment of panels in the PAB. Given the review of the literature characterised in the previous sections, the following research questions were developed to guide this study:

> RQ1: What is the most appropriate type of pull-system for the case jobbing environment?
>
> RQ2: What is the most appropriate detailed design of the selected pull-system for the case jobbing environment?

4. Methodology

4.1. Research strategy

Because of the nature of the research question and the desire to conduct an empirical enquiry that sought to explain a contemporary phenomenon in a real-life context using multiple sources of evidence, the case study was selected for the research strategy (Yin 2003). The case study can provide rich knowledge of a specific context (Meredith 1998; Yin 2003; Sousa and Voss 2008) and has a heritage within both Operations Management and Logistics where it has been employed for research purposes that include exploration, theory building, theory testing and theory extension (Eisenhardt 1989; Ellram 1996; Voss, Tsikriktsis, and Frohlich 2002). The case study reported upon in this paper was purposively selected (Silverman 2000) and was a longitudinal study conducted over a two-year period.

4.2. Research design and data collection procedures

This project was championed by the firm's senior management team. A project team was formed and a large room was dedicated to them for the duration of the study. The team had at its core six managers drawn from a cross-functional range of the resource and support areas found within work centre WC2. The researchers worked in a facilitation role, aided by VehicleCo accounting department staff who were tasked with responding to cost information requests. A simulation modelling expert was also seconded to the team. Figure 1 illustrates the two-phase research design model that was developed to act as a framework for the collection and analysis of the data, and to enable the research question established in the previous section to be answered.

Phase-1 of the study was conducted over a 20-month period and encompassed the design of the planned process improvement intervention within WC2. This entailed three constituent stages of research. Stage 1.1 was designed to provide the researchers with an understanding of the salient features and performance of the WC2 operation, and to act as a team building exercise for the newly constituted project team. The stage was initiated with a two-day structured workshop that involved the whole project team, and this was complemented by follow-up interviews and observation of shop floor practices to validate details raised during the workshop. The focus of this activity was the collective production of a VSM of the type popularised by Rother and Shook (1998). This was used as a vehicle for the application of methodological pluralism, whereby multiple data collection instruments were used to generate and triangulate data about the observed phenomena (Denzin 1970). These instruments included document and archival analysis, 140 photographs, and interviews and participant observation of all the resource centres within the focal work centre.

The purpose of Stage 1.2 was to capitalise upon the insight gained during the preceding stage and use this to help determine the most appropriate type of intervention for the case scenario and hence answer RQ1. The evidence collected was analysed by the researchers who

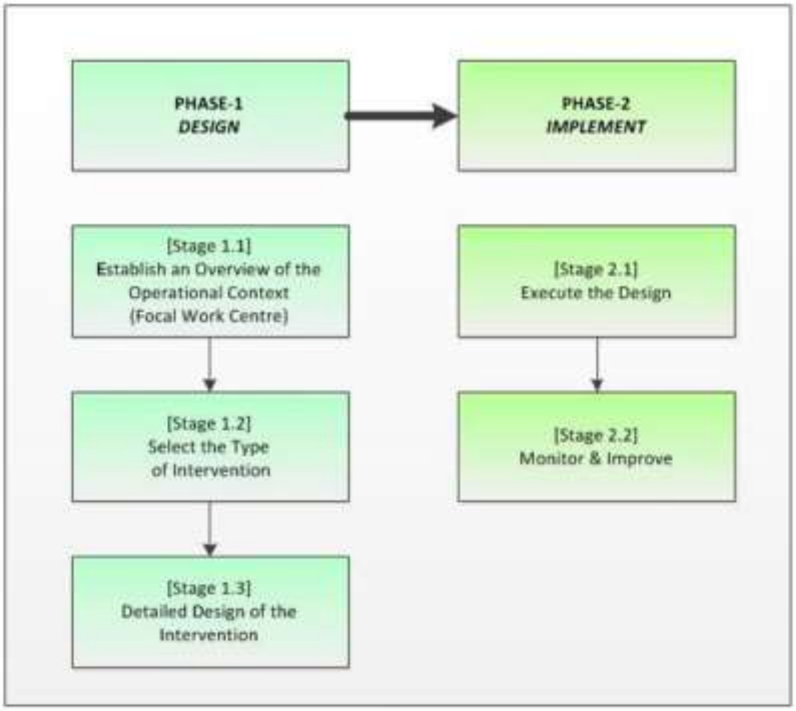


Figure 1. Research design.

subsequently decided that this should entail the implementation of a production pull-system, and that the most appropriate type of pull-system given the characteristics of the production environment was DBR (see Goldratt and Cox 1984). It was therefore necessary to extract and manipulate very large data files from the firm's MRP system to first identify the Drum (most highly constrained) resource. This in turn entailed the researchers developing and building their own bespoke capacity planner, WIP monitor and simulation model software tools in order to triangulate their evidence to establish the identity of the Drum. Having achieved this, Stage 1.3 involved the detailed design of the wider DBR device to address RQ2. This for example included the detailed calculation of the required Buffer size drawing upon historical breakdown records for the resources upstream of the Drum, and also the mechanism to be used to implement the Rope signalling device. Once completed, a modelling exercise was conducted to establish the likely impact of this planned DBR intervention, and a business case was developed from this. The DBR design and associated business case were duly presented to VehicleCo's senior management team and approval was granted for its execution.

Phase-2 was conducted over a four-month period and entailed the implementation and monitoring of the detailed DBR design developed during Phase-1. An external specialist was employed to further refine the capacity planner and WIP monitor tools (above) and the insight that they provided, and two of VehicleCo's specialist Lean experts from their internal Lean process improvement team were also allocated to the project for its duration in order to support the implementation. As a consequence of the resources and support afforded it, the DBR design developed during the previous stage of the study was rapidly implemented over a four-week period [Stage 2.1]. The performance of this pull-system was carefully monitored and improved over a further threemonth period [Stage 2.2] using the newly refined tools (above), and a number of small refinements were made to enhance its operation and control. By the end of this period, the new DBR system had become embedded in VehicleCo's standard production system.

4.3. Confidentiality

Under the terms of a confidentiality agreement, a threeyear moratorium on publication has been observed for this study. Other measures have also been applied within this paper to assure the anonymity of the firm whilst simultaneously maintaining the integrity of the findings. These measures include the use of the alias 'VehicleCo' for the case firm, and the disguise of all terminology that could be used to identify it. This includes all specifics regarding the firm's product portfolio, the industry sector within which it operates, its geographic location and all reference to its annual turnover and scale of employment. Lastly, all financial and operational data have been disguised by means of a constant modifying factor.

5. Discussion

5.1. Phase-1: design

To implement the first stage of the research design that was detailed in the previous section, the researchers decided that the most effective way to deepen their understanding of the WC2 operation was to construct a VSM of the type suggested by Rother and Shook (1998). Such an approach would also help forge good working relationships with the most influential figures on WC2's shop floor and management. The VSM technique has been used and described in numerous Lean projects and publications over the previous decade (see e.g. Seth and Gupta 2005; Abdulmalek and Rajgopal 2007; Serrano, Ochoa, and De Castro 2008; Lasa, De Castro, and Laburu 2009; Gurumurthy and Kodali 2011). The production of the VSM was subsequently approached in a conventional, highly interactive manner as suggested by the authors. This entailed directing the newly formed WC2 project team to use coloured pens, paper and sticky notes to produce a single landscape orientation diagram that described the current state of the whole WC2 operation; from supply of raw material through to delivery of completed bodywork and auxiliary panels to its downstream customer. First, the physical flow was drawn. The supplier and customer icons were noted on the map, and then each of WC2's resources (machines/ work centres) was represented as a single sticky note. Inventory points (WIP) were also noted using a different shaped and coloured sticky notes. Next, the information flow was drawn, with the production control system and all scheduling points noted on the diagram.

Conventionally, the VSM technique suggested by Rother and Shook (1998) is used for describing the flow of material and information of a single representative product line/family through its entire production pathway in order to act as a blueprint for the subsequent process improvement activity. Whilst a useful starting point, the project team found that this conventional VSM technique significantly under estimated the influence on the information flow on the observed manufacturing flow and performance. Having already constructed such a map, the team consequently focused on an elaboration of the information flows and then annotated the work-flow pathways for all 20 of the main factory product line contracts that flowed through WC2's production resources; adopting a unique colour code for each of these 'value streams'. This innovation yielded two particularly useful insights. The first of these was insight into the influence of the MRP and shop-floor data capture systems, and how they combined in the calculation of operational start dates. However, more importantly, this innovation highlighted the shared resources within this work centre.

The resultant map was 15-m long and reflected the complexity of this panel fabrication process. However, the team was able to translate the 200 colour coded contracts into four generic types of panel that were produced within WC2; each of which had a distinct route through the centre's 68 resource centres and formed a multi-contract workstream. These were termed Bonded Bodywork, Non-bonded Bodywork, Bonded Auxiliary and Non-bonded Auxiliary (bonded panels contain multiple parts that are glued together). This analysis facilitated the production of a schema that is conceptually similar to the familiar London Tube Map, with its simplified representation of underground rail lines (value streams) running through stations (resources). This is reproduced in Figure 2 and it is useful to briefly review its salient features.

WC2 receives raw material such as sheet metal from external suppliers, and produces a large variety of individually unique bodywork and auxiliary panels that are dispatched to the downstream customers for subsequent final assembly into whole bodywork and auxiliary structures. Therefore, whilst the VehicleCo operation as a whole could be described as an A-plant (after Goldratt 1995); the WC2 facility is a V-plant within this. It is a jobbing environment and is characterised by irregular demand, small order quantities, large variations in both the physical size and work content of panels, a deep BOM (particularly for bonded panels) and expensive materials. Panels are conveyed around the centre by means of the 'panel bar' system. This is an overhead rail that runs between each of the production resource centres and contains a number of panel bar 'hooks' onto which panels are attached for material handling purposes. The attached panels are manually pushed to the next resource in the production sequence, unhooked, processed and then re-attached to the panel bar.

Completed auxiliary panels are dispatched directly to the Auxiliary Assembly facility. Completed bodywork panels are [usually] dispatched to replenish panels that had previously been consumed from the downstream PAB, as scheduled by the firm's MRP system. However, on occasion bodywork panels might be dispatched directly line side to the relevant production line in the bodywork assembly area if, for example, expediting was required. Bonded panels represent the more complicated of the two types of workstream and therefore form the basis for the following summary of the WC2 production process.

Bodywork panel production starts with the processing of sheet metal into the correct panel shape at a machine in the resource centre called 'Forming'. This is the gateway resource and contains three separate machines of differing sizes. Auxiliary panels tend to be smaller and are kitted out in the Kit Store area. After forming, the panels enter the Masking booth where a robot sprays one side of the panel with masking material. The panels are then conveyed using the panel bar system to the Laser Scribe machine where the requisite pattern is etched into the masking material. This material represents protection in the subsequent Chemical Milling process, so this scribing pattern determines the thickness of panel material that will ultimately be milled away. Weight is an important design criterion, so panel thickness is reduced in areas where enhanced structural strength (e.g. a structural pillar location) is not required. After Chemical Milling, the panel makes its way to the Clean Line where it is dipped as part of a batch into a number of tanks to clean off the corrosive chemicals from the milling process and prepare it for painting. Once dry, the panel is conveyed into one of two booths where it is sprayed with paint primer material. Next, the primed panel is conveyed to the relevant sub-area of the Film Room where all the parts to be bonded to it are carefully positioned in situ; separated by adhesive ‘film’.

Again as part of a batch, this is transported to one of three large Autoclave ovens. The size of these ovens is a function of the size of the panels that they must physically accommodate. Here, the batch is cured under high pressure for a pre-designated period of time to bond the parts together and ensure the integrity of the adhesion process. The cycle time for this curing process is therefore the same regardless of the number of constituent panels in the batch, and is impervious to changes in customer demand rate, or takt time. After subsequent testing, the panel batch is moved to one of two six-axis CNC Routing machines where various sized and shaped cavities are cut out. Having already been primed, the panels are then conveyed to the paint shop for painting before lastly being dispatched to the relevant downstream customer destination as indicated earlier.

This initial mapping exercise therefore indeed proved useful to the team for deepening their understanding of the operational characteristics and throughput within WC2. It highlighted that most of the manufacturing resources used for panel production within this centre are in fact shared, and not dedicated to any single downstream contract or production line. It also highlighted that many of these resources such as Chemical Milling, Clean Line and Autoclaving are natural batch processes that are configured for the simultaneous processing of multiple, rather than single, panels.

5.1.1. Pull-system selection

Having gained the above insight, the next consideration was the selection of the most appropriate pull-system method for regulating the amount and flow of WIP through the centre. This was determined to be the method that would provide the highest service level to the downstream customer, with the shortest lead time. The three most influential and commonly implemented pull-system methods as suggested by Bicheno (2004) were now evaluated in turn for this case production environment: Kanban, CONWIP and DBR.

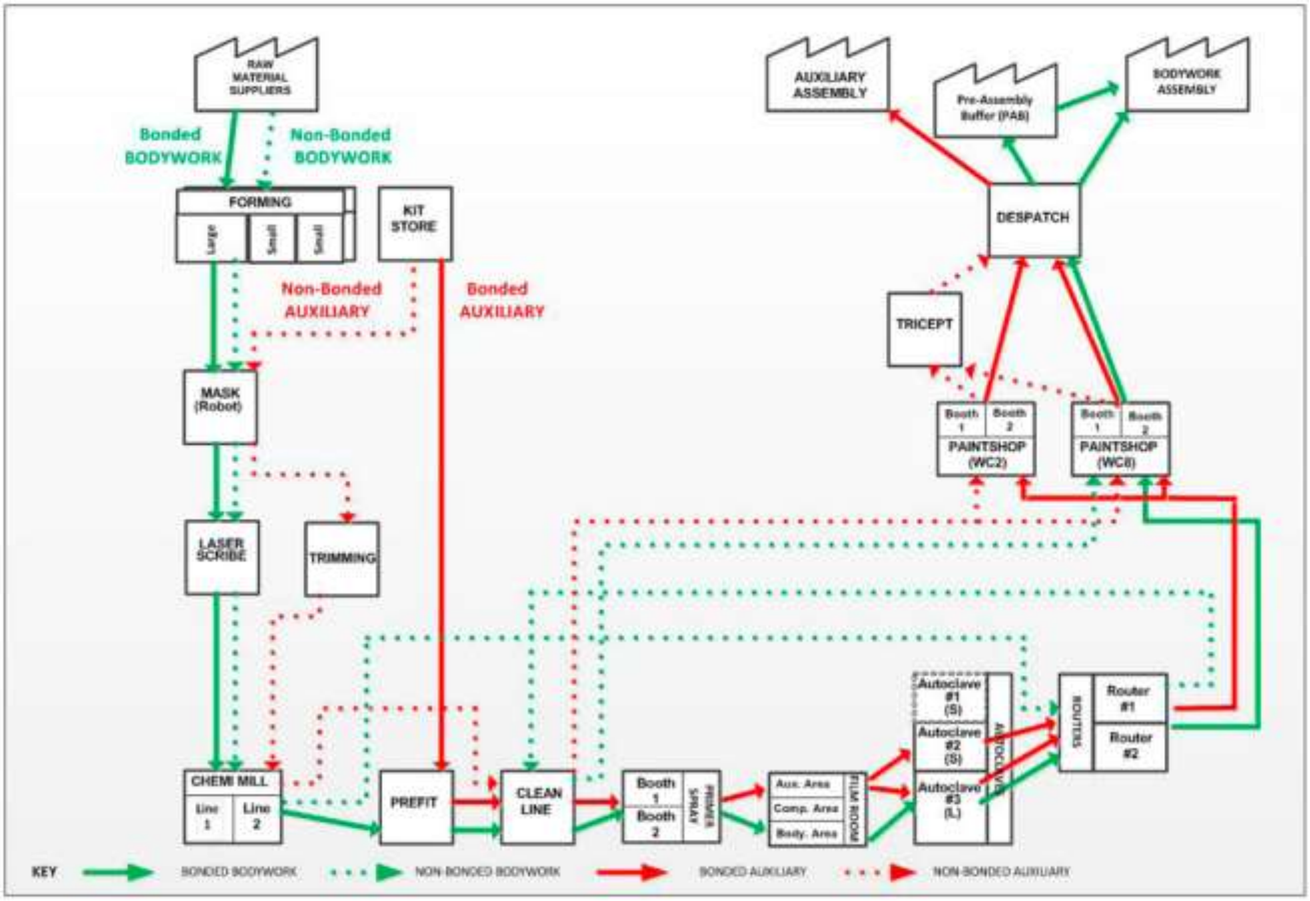


Figure 2. Schematic representation of the WC2-Metal Bond fabrication process.

The insight gained from the analysis of the data yielded during the previous stage of the study quickly established that a kanban pull-system as characterised in Section 2.2 would be infeasible. Kanban is a stock-based method and clearly implied that expensive bodywork and auxiliary panel parts would need to be replenished speculatively into supermarket areas post consumption in the hope that future demand would consume them. This implied prohibitive space and cost implications for implementing the necessary supermarket storage given the high material cost, deep BOM, large number of parts, large number of engineering changes, and large variation in the size and work content the panels. Likewise, these characteristics taken in conjunction with the irregularity of the demand for the panels produced within the centre made this an unsuitable application for the pacemaker concept.

A time-based scheduling method such as CONWIP or DBR was therefore considered to be the only feasible alternative in such an operating environment. Next, a CONWIP pull-system (after Spearman, Woodruff, and Hopp 1990; Hopp and Spearman 1996) was considered. However, CONWIP was rejected because the complexity of the work routings, amount of work content and lead time variation observed in this process was deemed to make it too unreliable in such a jobbing environment. Instead, the team established that DBR (Goldratt and Cox 1984) was the most feasible type of pull-system for the WC2 operating environment, and hence answered RQ1.

This conclusion marked the start of Stage 1.3 of the study. According to the Five Focusing Steps framework offered by Goldratt and Cox (1984), it was necessary to first identify the Drum that was to form the focal point for the pull-system design if a DBR pull-system was to be implemented. However, it was rapidly established that VehicleCo's MRP system could not facilitate this first step. Whilst it described well the labour content of work, it failed to accurately describe the equipment capacity of the many natural batch resources within WC2. It was therefore necessary for the team to develop a new standalone time-based capacity planning tool that could be used to identify the current and future constraints that were to be exploited in a DBR system. The resultant tool was developed using Microsoft Access and Excel and used the extracted BOM, routing and resource files from the firm's MRP system as input. Supplementary demand, shift pattern, scrap & rework rate data were also collected by the team and incorporated into the new tool. Lastly, the team codified and incorporated the batching rules that were in use within the plant for establishing the demand on WC2's natural batch resources. For example, the cure profiles and cure time slots for the Autoclave Ovens and the part size and dimensional capacity of the load for the Clean Line.

The resultant tool could produce a utilisation analysis of all the resources within WC2 for any selected demand/shift period within the order book horizon. For the period concerned, it calculated demand in hours for every WC2 resource. It then compared this demand against that resource's available hours in that period to yield a utilisation percentage figure. After modelling a large number of different weekly, monthly and annual time periods, the same four resources were found consistently to be the most highly utilised, and therefore candidates for being the Drum (Figure 3). These were the Laser Scribe, Clean Line, Autoclave Ovens and Router.

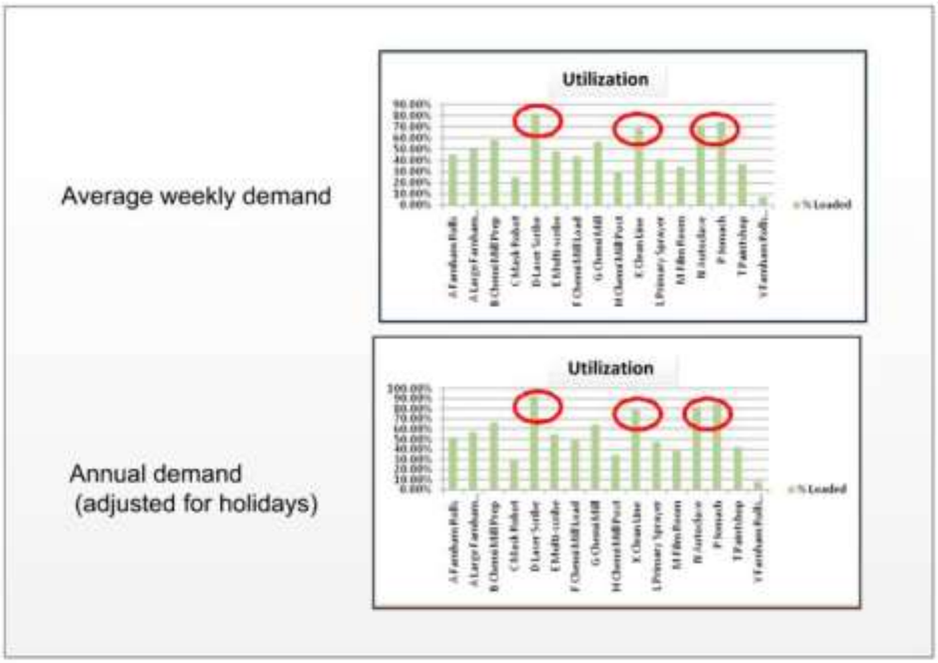


Figure 3. Capacity planner utilisation analysis – four consistently highly utilised resources.

In order to triangulate the findings of the capacity planner, and hence help establish which of the candidate resources was the Drum, a WIP monitoring tool was developed in Excel. This used a large data file extracted from the MRP system that provided the itemised location of every piece of WIP within WC2 at a snapshot point in time. It then compared this data against the resource and demand files to calculate the total WIP pieces, material value and average sales coverage of inventory (termed 'daysworth') at each of the following levels of granularity: resource, work stream (bonded or nonbonded bodywork/ auxiliary) and the aggregate for the whole of WC2. Seventeen such WIP snapshots were processed over a 16-week period to provide a longitudinal analysis of the WC2 WIP profile. By the end of this exercise, the identity of the Drum was still indeterminate, although it did make it possible to discount the Clean Line as a candidate. This WIP monitoring exercise also yielded other useful insights. For example, it was found that during the 16-week period of monitoring, total inventory within WC2 varied between 40 and 53 days worth of sales cover. This equated to a material and utility cost (MAUC) valuation of £1.1–£1.4 million; or £2.8–£3.4 million valuation in fully absorbed standard costing (FASC) terms. Information on the average time taken to serve the downstream customer was also refined; with panels found to take between 20 and 26 days to get through the WC2 fabrication process.

With the help of a simulation expert seconded to the team, a simulation model of the WC2 panel production process was then built using the DELMIA software suite. Figure 4 illustrates a screen dump of this model, which took as its starting point a blueprint of the WC2 plant. Onto this were plotted the various production resources and bonded and non-bonded WIP inventory points. Using the data collected during the study the model could then demonstrate throughput of panels and the ebb and flow of WIP over the passage of time, with WIP being colour coded by type and represented as a dynamically moving histogram superimposed on the blueprint. On the left-hand side is a tabular representation of the capacity planning tool and its utilisation analysis results, with the three consequent candidate Drum resources highlighted on the screen dump. The key findings from the WIP monitoring exercise are summarised on the bottom, indicating the financial and lead time current state of the WC2 process and hence the scale of potential for a successful DBR implementation.

Both Figures 3 and 4 illustrate that even though the Laser Scribe was the most highly utilised resource, the other two Drum candidates had reasonably close utilisation figures. As emphasised by Hopp and Spearman

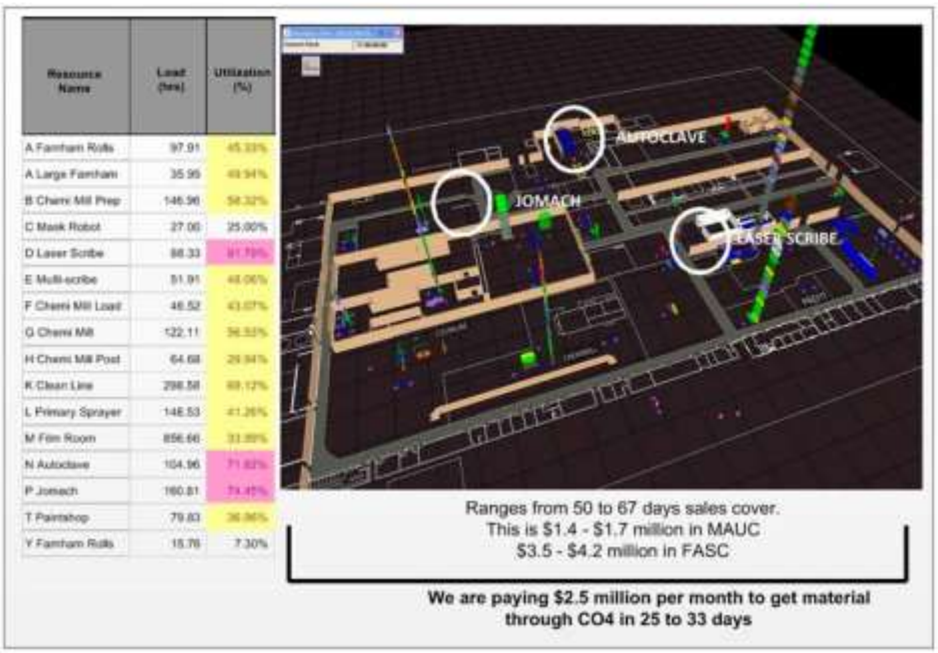
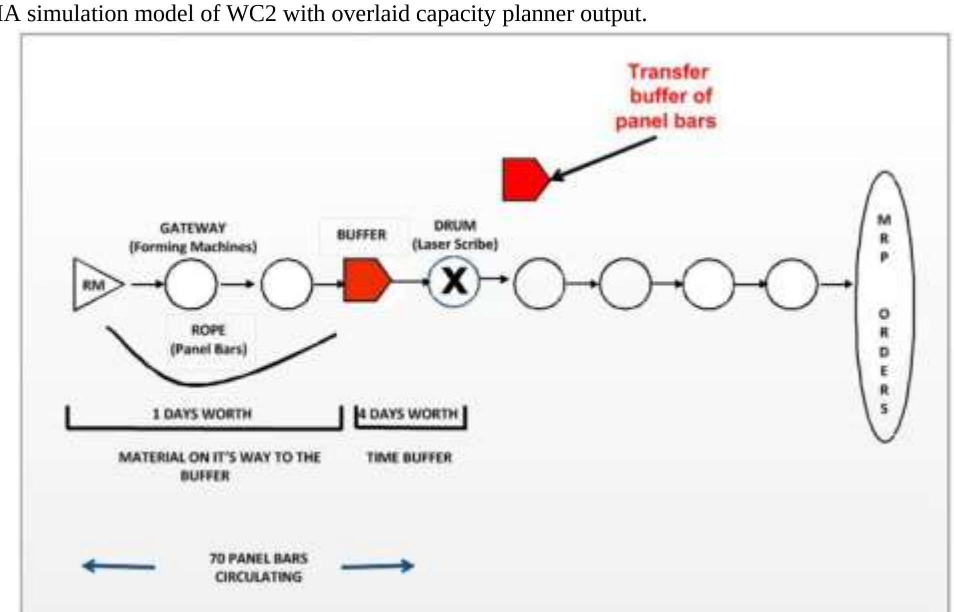


Figure 4. DELMIA simulation model of WC2 with overlaid capacity planner output.



(1996), such a situation demands an understanding of the relative variability experienced by such resources. The coefficient of variation (COV) was measured for the lead time characteristics of the whole WC2 production system and included all part numbers. The COV for all three Drum candidate resources was found to be high; being in excess of 0.5. It was observed that all panels flowed through the Laser Scribe, but diverged into bonded and non-bonded routes after this point before then flowing onwards and converging through the other highly utilised resources. Given this scenario, the team adhered to the rule when bottleneck feeds bottleneck it is best to deal with the first one first (anon.). They consequently determined to use the Laser Scribe as the Drum, as creating the sequence sensitive scheduling point here would also induce better flow characteristics for the Autoclaves and the Jomach.

5.1.2. DBR design

Figure 5 illustrates the resultant DBR design at VehicleCo, and hence represents the answer to RQ2. This is a conceptual diagram that does not attempt to accurately reproduce all of the resources upstream and downstream of the Drum. In fact, reference to the schematic representation of the WC2 fabrication process (Figure 2) reveals that the Laser Scribe (Drum) is located relatively early in this production process. This means that the Rope loop between the Drum and the gateway resource centre (Forming) covers a relatively short upstream span. It was not possible.

With this potential configuration limitation in mind, the next step of the design process was to establish an appropriate Buffer size to ensure that the Laser Scribe never had to stop working due to the failure of a feeding, upstream resource. WC2's breakdown records and downtime reports were made available, and the information was input into the DELMIA simulation model built earlier. Given the variation that was exhibited, it was calculated that a buffer of two daysworth of work would be sufficient to protect the Laser Scribe and hence enable it to exploit its capacity to the full. However, demand on WC2 was projected shortly to increase due to the enlarged order book. A business case was subsequently developed by the team for adding a Laser Scribe shift at the weekend in order to service this additional projected demand (but not the feeding resources for reasons of expense). This situation necessitated an increase in the Buffer size to four daysworth in order to cover this weekend shift and ensure that approximately one daysworth of Buffer inventory was still in place at the start of the Monday morning shift. After calculating what four daysworth of panels represented in a physical sense, it was then validated that this Buffer size could be physically accommodated in the designated WIP area in front of the Laser Scribe machine.

A convenient Rope signalling system was found to already exist within WC2 in the guise of the panel bar material handling system. The panel bar mechanism had two desirable attributes in this role. The first was that it lent itself readily to act as a long-distance mechanism for signalling permission from the Drum (Laser Scribe) to the gateway resource centre (Forming) to release the next scheduled tranche of work into the system. The physical presence of a panel bar at the forming centre acted as the permission signal. An important point to stress is that this schedule sequence of the next panel work order to release was still driven by the due date required by the Final Assembly operations downstream of WC2 and was provided via the firm's MRP system. The new DBR design merely ignored the launch dates provided by the MRP system and instead finite forward scheduled from the current point in time. The second desirable attribute of this Rope mechanism was that it could also be used to physically limit the number of panels (daysworth of WIP) within the WC2 fabrication system by controlling the number of panel bars in circulation on which it was possible to hang these panels. After extensive calculation, it was determined that the four daysworth of panels in the Buffer and one daysworth of material in the resources upstream of this Buffer equated to 70 panel bars in circulation within the loop between the Forming machines and Laser Scribe.

The final WC2 DBR design consideration was the number of panel bars it was necessary to include in the 'second loop' to transport the panels processed by the Drum downstream to the exit (Despatch) area. There was significant process variation in the downstream resources such as Chemical Milling and the Clean Line due to issues such as uneven shift patterns, scrap/ rework rates and their natural batch characteristics. There was consequently a risk that under certain circumstances, the Drum might be unable to offload the panels it had produced to the downstream resources due to lack of panel bar availability; hence reducing the system's throughput. A Transfer Buffer was consequently established. This was a pool of surplus panel bars in the second (post Drum) loop that was only to be used in the advent of such a problem jeopardising the Laser Scribe's output. It required special managerial permission to use this Buffer. As per the time-based work, Buffer in front of the Laser Scribe, the size of this Buffer was a direct function of the variability within the resources constituting the loop. Again, a conservative calculation of this initial Buffer size was adopted so as not to risk confidence in the DBR intervention. Buffer monitoring procedures were also put into place. The plan was to then reduce the size of these Buffers over time as the process variability was reduced due to developments such as shift pattern changes, quality improvements and improved machine reliability. This approach further reduced WIP and hence overall MLT, and ensured minimal risk of Buffer failure.

5.2. Phase-2: implement

The initial target for the DBR design produced during the previous phase of the study within WC2 was to reduce MLT time as measured by WIP by 20%, whilst simultaneously improving the service level to the downstream customers. Even though the design of the chosen pull-system was recognised to have the limitations discussed earlier, the actual performance of the implemented DBR system exceeded the target expectations. Three months after the initial implementation went live and was subject to a number of minor modifications, the performance of the new system was evaluated and compared against the baseline performance established at the implementation date. The total number of panels in WC2 was found to have reduced from 346 to 139 (60%). When converted into inventory coverage, this equated to a reduction from 32 to 14 daysworth (56%), which translated into an increase in WC2's inventory turns from 9.1 to 21.2. In addition, the average number of jig stoppages per week in Final Assembly that were attributable to WC2 dropped from six to less than one.

The impact of this performance was formally valued by the VehicleCo accounting department to equate to a £450 K MAUC reduction; or £850 K in FASC terms. These figures were based upon the traditional management accounting approach that sees such inventory reduction as a one-off gain. It excludes any valuation of the other ongoing benefits that are implicit in such a WIP reduction initiative. For example, the reduction in the obsolescence and write-off costs attributable to engineering changes or the reduced need for premium paid overtime due to the level of responsiveness of the new system. The real financial value of the project was therefore significantly higher. As a consequence of this significant economic impact, the WC2 DBR project was nominated by VehicleCo for its parent enterprise's annual worldwide process improvement competition in 2009, and it won the first prize. This performance poses the question: should 'flow' be the first principle of Lean (after Womack and Jones 1996)?

As indicated in the research methodology, strict confidentiality criteria remain in place regarding this work. However, it is possible to confirm that during the passage of time between the original implementation and the writing of this paper, this DBR implementation has been refined and improved upon. VehicleCo are currently in discussion with one of the authors regarding the design and implementation of a pull-system for a new facility.

6. Conclusions

At the outset of this paper, it was established that, whilst a variety of pull-system methods exist, the pull-system concept is often conceived as being synonymous with the kanban method (Hopp and Spearman 1996); particularly within the Lean community. It was also established that there was a lack of coverage within the literature on the subject of Lean implementation within a jobbing environment, and a notable gap concerning the relationship between Lean manufacturing and the management of shared resources. The objective of the research reported upon within this paper was consequently to select, design and successfully implement an appropriate pull-system for the case jobbing production environment in order to contribute to this dialogue. The resulting applied research project was conducted over a two-year period and entailed a two-phase research design.

The first phase of the study encompassed the main academic contributions of this paper. The first such contribution was the development of a novel mapping tool that described the routings of multiple value streams (Figure 2), and the resulting map highlighted that most of the manufacturing resources used for panel fabrication were in fact shared batch resources that were not dedicated to individual contract value streams as the Lean literature would suggest. The subsequent analysis established that the most viable pull-system for the production environment that this described was Goldratt and Cox's (1984) DBR method. Detailed design work revolved around the researchers developing bespoke capacity planner, WIP monitor and simulation model software tools (Figures 3 and 4) to first identify the Drum (constraint), and then undertake the work necessary to produce a practical DBR design concept for this case context (Figure 5). Therefore, this paper contributes significantly to the literature that is available on the relationship between the Lean paradigm and the management of shared production resources, and adds to that on the detailed design and implementation of a DBR pullsystem in a jobbing-type environment.

The second phase of the study entailed the implementation, monitoring and improvement of this DBR design and embodied its practical contribution and impact. The resultant intervention exceeded its forecast improvement targets and represented notable commercial benefit for the firm. It reduced WIP in the panel fabrication plant by nearly 60%. This equated to a 57% reduction in MLT and more than doubled the inventory turns. Importantly for an industry characterised by penalty clauses for late delivery, the intervention resulted in greatly improved delivery schedule adherence to the downstream PAB and Final Assembly customer. The financial benefit of this performance was independently audited to amount to £850 K per annum. On the basis of this level of operational and financial impact, the DBR intervention project at WC2 was awarded the first prize at the annual worldwide process improvement competition that was held by the parent enterprise. It has also proved to be sustainable; having subsequently been refined and presented as a template for roll-out to other parts of VehicleCo's business.

Given this audited impact, it is possible to conclude that adopting a deterministic, teleological approach to process improvement is a fallacy. The study reported upon in this paper was initiated under the aegis of a Lean initiative. If such a teleological approach had been adopted in this case it would have led to an attempt to implement a kanban pull-system within WC2. Such a system was not viable given WC2's operating characteristics. It is therefore irrelevant that DBR is derived from the TOC rather than Lean paradigm. This underlines the importance of contextual alignment and results over dogma and the application of paradigm brand labels, as the latter approach leads to orthodoxy and sub-optimal improvement performance.

Whilst the study reported upon in this paper resulted in the academic and practitioner contributions summarised above, a number of limitations are recognised. For example, the panel production schedule was determined by the PAB rather than Final Assembly. In addition, further work is required to explore the issues that pertain to the relatively upstream location of the Drum in this DBR implementation; such as the affect on Drum location of breakdowns and other causes of variation within the downstream resource centres. Likewise, a future paper is planned to more fully develop the discussion regarding the appropriate 'fit' and relative merits of the application of CONWIP compared to DBR in a case such as VehicleCo's. This paper will also consider adaptations, such as the use of multiple CONWIP loops. As a final comment, it should be noted that although this case study was purposively selected and longitudinal in nature, some caution is advised in generalising its findings. Consequently, having first addressed the issues above, future research will aim to replicate this study in a number of different jobbing environments to test its efficacy. It is also intended to synthesise and test a generalisable method for targeting and implementing improved product flow and throughput in manufacturing environments from the techniques developed by the researchers during their two related research projects at VehicleCo.

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