S-DBR DESIGN, IMPLEMENTATION AND CRITICAL EVALUATION USING ACTION RESEARCH

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Copyright Statement

Abstract

This research aims to explore and bridge the contradicting views of both academic researchers and practitioners on Simplified Drum-Buffer-Rope (S-DBR). Having evolved from Drum-Buffer-Rope (DBR), S-DBR is the latest Make-To-Order (MTO) Production Planning and Control (PPC) solution introduced by Theory of Constraints (TOC) practitioners. Reviews by academics doubt the suitability of DBR as a PPC in MTO. Instead, Workload Control (WLC) is advocated as the most appropriate PPC application.

The appropriateness of S-DBR in generic MTO environment is critically evaluated through theoretical arguments. This is followed by a real-life S-DBR implementation through action research (AR). The purpose is to capture practical knowledge on how S-DBR is reconfigured according to contextual requirements.

It is found that previous reviews reduce DBR into a mere *bottleneck* or *constraint* rule. This ignores the *buffer management* concept, a critical concept in TOC applications. This research re-evaluates and advocates S-DBR, together with its three critical concepts: *constraints management*, *buffer management*, and *load management*, as an appropriate PPC in MTO environment.

Although both S-DBR and WLC have different origins, they can be represented on a continuum of *planning* and *execution* with S-DBR on one end: *light planning*, *heavy execution* and WLC on the other end: *heavy planning*, *light execution*. The potential incorporation of *buffer management* in WLC implementation is also proposed and explored.

Through AR cycles, an S-DBR solution is successfully redesigned to overcome contextual challenges such as high touch time, wandering bottleneck, and parallel machine route. It has also embedded informal practices, incorporating human roles, and is developed into a decision support system and communication platform.

A year after implementation, this solution successfully exposed hidden resources, reduced operation cost by half, and facilitated senior management to empower shop floor personnel, recognising them as an integral part of the intervention solution.

Publications/Conferences

Part of this research has been submitted for the following:

Practitioner Conferences

1. YEONG, A. and STRATTON, R. (2016). Preparing for growth. In: 28th International Conference of the TOC Practitioners Alliance (TOCPA), Northampton, November 2016.
2. YEONG, A. and STRATTON, R. (2017). Applying Linear High Touch (LHT) Time to MTO Rotary Moulding with Planned Load. In: TOCICO 2017 International Conference, Meliá Berlin, Berlin, Germany, 16 – 19 July 2017.

Conference Proceedings:

1. YEONG, A. and STRATTON, R. (2017). Capturing Action Research Knowledge through Strategy and Tactic (S&T) Tree. In: EurOMA 2017: 24th International Conference of the European Operations Management Association, Heriot-Watt University, Edinburgh, 1-5 July 2017.
2. STRATTON, R. and YEONG, A. (2018). The design and implementation of a WLC system incorporating time buffer signalling: an action research study. In: EurOMA 2018: 25th Annual EurOMA (European Operations Management Association) Conference, Budapest, Hungary, 24-26 June 2018.
3. YEONG A. and STRATTON, R. (2018). Enabling small firm growth through process innovation – a reflection. In: 25th Innovation and Product Development Management Conference (IPDMC), Porto, Portugal, 10-13 June 2018.
4. YEONG, A. and STRATTON, R. (2018). Human factor: the bridge to a successful intervention in MTO (Make-To-Order) manufacturing environment. In: EurOMA 2018: 25th Annual EurOMA (European Operations Management Association) Conference, Budapest, Hungary, 24-26 June 2018.

Part of this research has been submitted and awaiting acceptance for the following:

1. YEONG, A. and STRATTON, R. (2019). The Appropriation of Trust for Successful PPC Implementation. In: EurOMA 2019: 26th Annual EurOMA (European Operations Management Association) Conference, Helsinki, Finland, 17-19 June 2019.

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Through KTP, Innovate UK has played an important role in creating the opportunity for a successful collaboration between University and Industry. Having completed a KTP successfully as an associate, I am honoured to be co-supervising with Roy in our next KTP.

Glossary of Abbreviations

5FS	Five Focusing Steps
BM	Buffer Management
BP	Buffer Penetration
BS	Buffer Status
CCPM	Critical Chain Project Management
CCR	Capacity Constraint Resources
CM	Constraints Management
COR	Corrected Order Release
CPCM	Contribution Per Constraint Minute
CPM	Critical Path Project Management
CRM	Customer Relationship Management
CRT	Critical Reality Tree
DBR	Drum-Buffer-Rope
DD	Due Date
DDP	Due Date Performance
DSS	Decision Support System
EC	Evaporating Cloud
ERD	Earliest Release Dates
FIFO	First In First Out
FRT	Future Reality Tree
I/OC	Input / Output Control
LM	Load Management
LOMC	Load Oriented Manufacturing Control
LRD	Latest Release Dates
LT	Lead Time
LTS	Lead Time Syndrome
LUMS	Lancaster University Management School
MBQ	Minimum Batch Quantity

MPS	Master Production Schedule
MTO	Make to Order
MTS	Make to Stock
OCD	Operation Completion Dates
OE	Operating Expenses
OM	Operations Management
OPT	Optimised Production Technology
ORM	Order Release Mechanism
ORR	Order Review and Release
PB	Production Buffer
PBB	Path Based Bottleneck
PL	Planned Load
PM	Project Management
PPC	Production Planning and Control
PRT	Prerequisite Tree
POOGI	Process of On-Going Improvement
QC	Quality Control
RB	Release Backlog
S&T	Strategic and Tactic
SA	Starvation Avoidance
SILT	Standard Industry Accepted Lead Time
S-DBR	Simplified Drum-Buffer-Rope
SLAR	Superfluous Load Avoidance Release (SLAR)
SME	Small and Medium Enterprise
SSL	Station Stock Limitation
TA	Throughput Accounting
TB	Total Backlog
TBL	Total Backlog Length
TOC	Theory of Constraints
TOCICO	Theory of Constraints International Certification Organisation

TP	Thinking Process
TT	Transition Tree
TW	Total Workload
TWC	Total Work Content
WIP	Work In Process
WLC	Workload Control

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Chapter 1: Introduction

Life is really simple, but we insist on making it complicated
- Confucius

1.1 *Fitness* First

The *applied* nature of Operations Management (OM) has witnessed the proliferation of OM best practices such as Total Quality Management (TQM), Just-In-Time (JIT) manufacturing which later evolved into Lean production (Womack et al., 1990), and Optimised Production Technology (OPT) which has later developed into Theory of Constraints (TOC) (Done et al., 2011; Voss, 2005).

The understanding of the *best OM practices* together with their boundaries is particularly crucial for SMEs (Small and Medium Enterprises) which usually has limited resources. SMEs have to be cautious not to fall into the trap of *copying best OM practices* to achieve *world-class performance* (Done et al., 2011; Gupta and Boyd, 2011; Schmenner and Swink, 1998; Stevenson et al., 2005). This is echoed by various researchers stressing the importance to identify the underlying philosophies, laws, theories and assumptions of *best OM practices* in the industry (Boer et al., 2015; Done et al., 2011; Hayes and Pisano, 1994; Hopp and Spearman, 2004; Sousa and Christopher, 2001; Sousa and Voss, 2008; Voss, 1995; 2005). The mixed results shown between adoptions of best practices and improved operating performance prompted Voss (1995, 2005) to stress the need to identify the *contextual dependencies* of these *best practices*. Research attention should focus on understanding the contextual conditions under which the practices are effective (Sousa and Voss, 2008). In addition, OM researchers have stressed the need to '*do a better job of defining their boundaries and applicability'* to have actual theory contribution (Boer et al, 2015).

This research aims to contribute by looking into the *fit* of Theory of Constraints (TOC) based Production Planning and Control (PPC) best practice in MTO environment. The next section details the origin of this research and an overview of this thesis document.

1.2 The *Genesis*

This research originated from a practical problem in Amberol, an SME manufacturing company. The senior management of Amberol has heard about the success of Theory of Constraints (TOC) and would like to implement a TOC based PPC solution through Knowledge Transfer Partnership (KTP). Being cautious of not to blindly copy any *best practice* (section 1.1), this research explores the *fit* between the proposed *best practice* and Amberol's contextual environment. Solutions will be developed to bridge any *non-fit* elements identified. Research questions are formulated as follows:

RQ1: What are the concepts underpinning S-DBR and how can they be configured to meet specific MTO contextual environments?

RQ2: What are the implementation issues in S-DBR and how may they be addressed?

This exploration begins by performing a diagnosis on Amberol's Make-To-Order (MTO) manufacturing environment (Section 2.1). In Section 2.2, a detailed diagnosis is performed on the company's manufacturing process. This provides an insight into the complexity of a seemingly simple rotational plastic moulding technic. By adopting a systemic perspective, Section 2.3 continues to explore the position of manufacturing department within the company's business process. Section 2.4 attempts to provide an insight into the working culture in Amberol before ending the diagnosis by providing a summary on challenges and issues faced by the company (section 2.5).

Chapter 3 attempts to address the research questions through theoretical arguments. It begins by conducting a review on appropriate MTO PPC solution (section 3.1). The findings show that Workload Control (WLC) is advocated by academic researchers as the most appropriate MTO PPC solution for SMEs (Small and Medium Enterprises). On the contrary, TOC based PPC application is being reviewed as inappropriate.

This finding is in contrast with the proliferation of TOC based PPC application in the industry by practitioners through organisations such as the Theory of Constraints International Certification Organisation (TOCICO). Noticing the gap between the perspectives of academics and practitioners towards TOC based PPC application, it is necessary to explore this gap with the attempt to bridge the two.

Chapter 3 continues to explore the underpinning philosophy, assumptions and mechanisms used in WLC (section 3.2) and TOC (section 3.3). Focus is given to review the latest development in TOC application in MTO: Simplified Drum-Buffer-Rope (S-DBR). Building upon the understanding developed in section 3.2 and 3.3, a comparison analysis between WLC and S-DBR is performed in section 3.4.

Existing reviews on PPC applications for MTO doubt the applicability of Drum-Buffer-Rope (DBR). In these reviews, DBR is largely reduced into a mere *Constraint Management* or *Bottleneck* solution. This has largely ignored the concept of *Buffer Management*: the signalling mechanism to be used alongside *Constraint Management* in DBR implementation. Although S-DBR has been introduced and practiced by TOCICO for over fifteen years, attention by academic researchers is limited.

In section 3.4, a critical review is attempted on both WLC and S-DBR. It is found that even though both originates from different philosophical underpinning, they exhibit various similarities. This is in resonance with the call by researchers for possible *cross-breed* research. At the end of the review, the author suggested the possibility of an S-DBR based WLC solution.

The first half of chapter 3 evaluates the relevance of S-DBR from a theoretical perspective. The second half of the chapter explores the challenges identified in previous reported WLC and S-DBR cases. The challenges can be broadly categorised into three areas. The first area is *best practice* specific. For S-DBR, specific implementation guide and issues are captured by practitioners in the form of Strategy and Tactic (S&T) tree (section 3.5).

The remaining two areas are *people* related and *technically* related. In view of the importance of *Human Role* (HR) in PPC, and the need to develop PPC into a *Decision Support System* (DSS), both elements are crossed into a *HR – DSS matrix* which could potentially be used as a guide in PPC implementation (section 3.6).

Section 3.7 continues to explore the performance measurements used in prior cases to evaluate WLC and S-DBR implementation. Apart from the traditionally used quantitative measurements, such as *time related*, *dependability*, *shop load*, and *financial related*, this research advocates the recent use of *qualitative evidences* by researchers to measure performance.

Based on the three essential elements highlighted in chapter 3: *Underpinning philosophy* (section 3.2 – 3.4), *Challenges in Implementation* (chapter 3.5 – 3.6), *Performance Measurements* (section 3.7), and the importance of *Contextual Requirements* (section 1.1), a conceptual framework is constructed to underpin this research (section 3.8). Through the conceptual framework, this research attempts to explore the *fit* between theory and practice of S-DBR, and to bridge the gap, if any.

Having arrived at a proposed conceptual framework to underpin the research, chapter 4 explores the appropriate research methodology to support the research design. This research is of dual purposes. The first purpose is to provide a solution for a practical problem. The second purpose is to capture the practical knowledge generated throughout the solution implementation process. To achieve the above purposes, section 4.2.1 – 4.2.4 explores the methodological fit and proposes Action Research (AR) as the most appropriate research approach to be adopted. Inherently, AR carries the same dual purposes as this research.

The intervention nature of this project places this research *in* action. It is necessary to *take action* to effect change. This is carried out through multiple cyclical processes with each consisting of *plan*, *take action*, *evaluate action*, and *construct* next cycle. Through action taken, knowledge is generated. Knowledge generated is captured through the formal supervisory committee setup for KTP, and four other informal groups. Each of the group is consists of various stakeholders (section 4.3.2). Data gathering is performed in both formal and informal settings. This includes minutes of meetings, field notes, interview notes, and direct observation (section 4.3.3). Details of research design is illustrated in section 4.3.

The main AR cycles throughout the three stages of intervention process are discussed in chapter 5. The three stages are *pre-change* (section 5.2), *in-change* (section 5.3), and *post-change* (section 5.4). In the *pre-change* stage, the assumptions used in generic S-DBR is challenged using Amberol's contextual environment. The *non-fit* found in two major assumptions leads to the redesign of time buffer and due date determination mechanism (section 5.2). Subsequent cycles include *Rethink Load Management* (section 5.3.1), *Avoid Optimising Below Noise Floor* (section 5.3.2), and *Rethink on the Role of Production Manager* (section 5.3.3). This is followed by the discussion on the cycles involved in developing the core modules of the prototype software (section 5.3.4).

During trial run, a shift in critical constraint resource happened. This leads to a *Rethink on Total Production Time* (section 5.3.5) which has exposed some overlooked assumptions in the solution design. It has also exposed an existing internal policy which is disruptive to the production flow. This subsequently leads to the next cycle: *Evolving into a Communication Platform* (section 5.3.6).

A year after implementation, company performance is evaluated using both quantitative (section 5.4.4) and qualitative (section 5.4.5) evidences. Quantitatively, the solution has exposed hidden resources in the company. This has resulted in a reduction in operational cost by half. Drawing from qualitative evidences, confidence towards the PPC software is demonstrated through its successful integration into the company's daily business routine. It has also introduced a new working culture, introducing a shift from *individual* effort to *team* effort. In addition, empowerment of shop floor personnel releases senior management to focus on business development.

The potential contribution of this research towards existing body of knowledge is discussed in chapter 6. The development of a new *S-DBR Strategy and Tactic (S&T) tree* for Amberol could potentially be used to inform companies with similar manufacturing environment (section 6.2). It could also potentially demonstrate how generic S-DBR can be easily adapted to suit contextual requirements. The complexity in manufacturing environment exhibited in this research potentially contributes towards the existing published S-DBR cases which have relatively simpler production characteristics. Potential contributions to other aspects of PPC and its implementation are described in section 6.3 – 6.4.

Adopting the *Engaged Scholar Diamond Model* introduced by Van der Ven (2007:10), the organisation of this thesis document is illustrated in *Figure 1.1*.

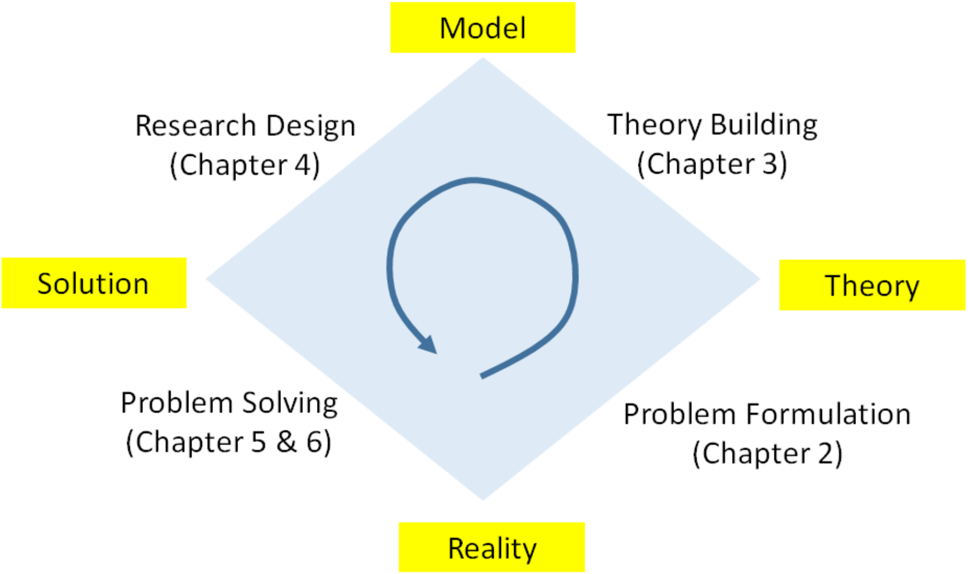


Figure 1.1: Organisation of this Thesis

Source: Adapted from Van der Ven (2007:10)

Chapter 2: Problem Formulation

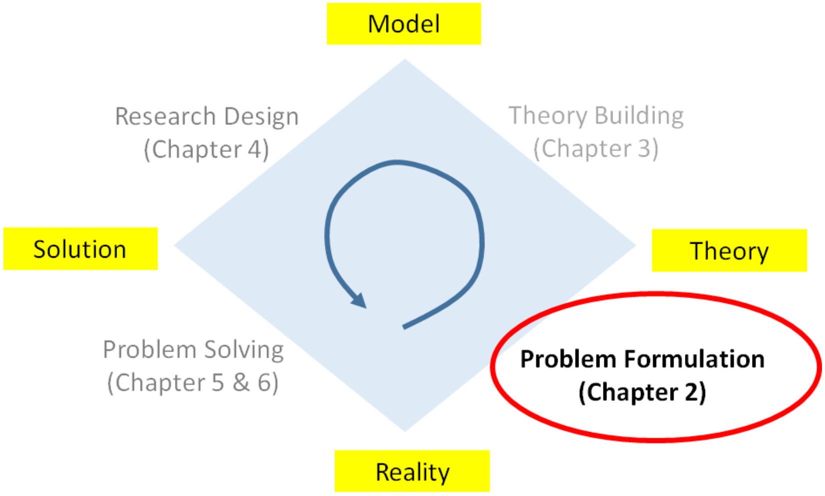


Figure 2.1: Organisation of this Thesis

Source: Adapted from Van der Ven (2007:10)

This research originates from a *real-life* problem of an SME manufacturing company, Amberol. To solve this *real-life* problem, the senior management has proposed the implementation of a TOC based PPC application: Simplified Drum-Buffer-Rope (S-DBR).

Acknowledging the importance of *fitness* between *contextual environment* and *best practice* (section 1.1), the following two research questions are formulated:

RQ1: What are the concepts underpinning S-DBR and how can they be configured to meet specific MTO contextual environments?

RQ2: What are the implementation issues in S-DBR and how may they be addressed?

This chapter aims to provide an insight into Amberol's contextual manufacturing environment, business operation, and working culture. At the end of this chapter, a summary of challenges identified in the manufacturing process in this company will be provided.

2.1 Amberol's Manufacturing Environment

Amberol is a small roto-moulding plastic manufacturer established in year 1977. More than twenty-five years ago, they pioneered the concept of self-watering hanging baskets and planters on the UK high street using their innovative Aquafeed^{TM} concept. Since then this family run business has extended its range to include decorative bins with some prestigious local authority customers, such as the City of Westminster. They are known for their innovative range with customisable features that distinguishes them from the competitors. Operating on make-to-order manufacturing strategy, the growing product range and complexity is increasingly difficult to manage. Coming off recession with the aspiration to take advantage of the emerging growth opportunities, the management has identified the need to put in place a manufacturing management system as a top priority.

Although the company has attempted to engage third party developer to provide manufacturing system, it did not meet their requirements. This is mainly due to the lack of internal expertise on planning and control system and the complexities in rotary moulding machines scheduling. The remainder of this section will explore the complexities in Amberol's manufacturing environment.

2.1.1 Rotational Moulding Process

Rotational moulding technique is a plastic moulding technology utilises casting technic to make hollow articles without exerting pressure. This reduces the cost in making moulds as it does not need to withstand pressure. Together with its flexibility in producing plastic moulded products without limitation in its size, it allows a wide range of applications.

As shown in *Figure 2.2*, rotational moulding process involves four main stages. This process starts by placing plastic, the raw material in the form of powder, into a mould. Upon closing the mould lid, it is sent into the oven to go through the second stage: *heating*. In the oven, the mould is being rotated at a predetermined speed along two axes. Through heating and the rotation movement, the melted plastic flows and forms a layer on the wall of the mould.

Once fully melted, it is moved to cooling chamber and enters the third stage: ‘cooling’. In this stage, the rotation of the mould continues until it reaches a predetermined temperature or time length where a solid plastic product is formed. In the last stage, the plastic product is removed from the mould.

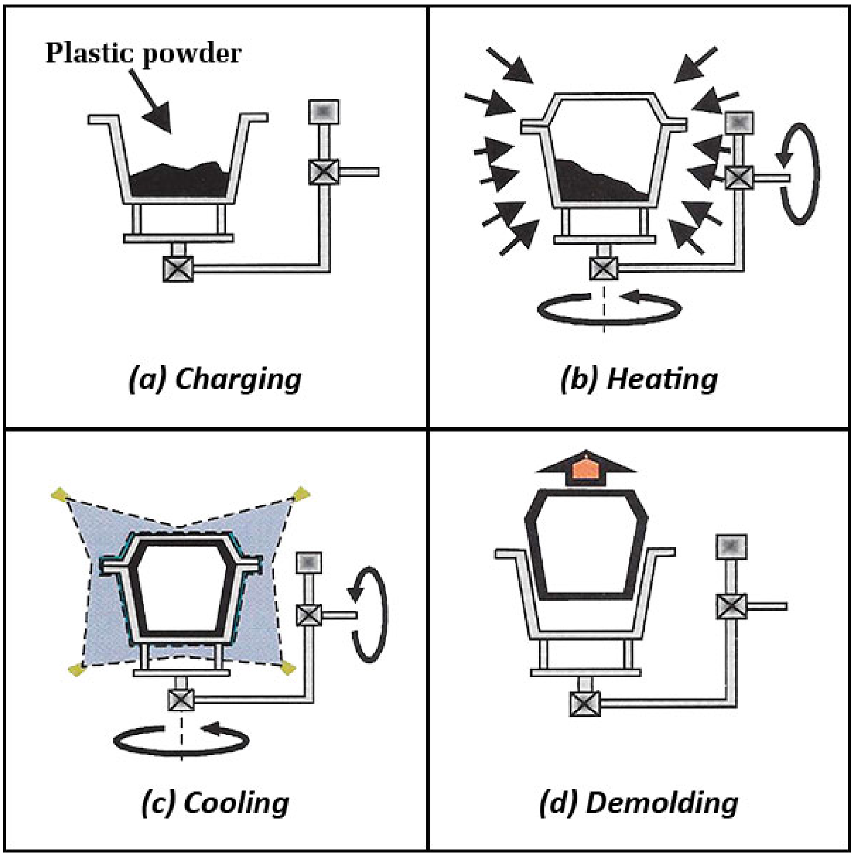


Figure 2.2: Moulding Process

Source: British Plastic Federation (2018)

On paper, the moulding process appears to be simple. In practice, the British Product Federation (2018) cautions that, ‘*it is in fact extremely complicated*’. This is due to the various variables which could affect production, such as ambient temperature, humidity, powder quality etc.

2.2 Amberol’s Manufacturing Process

Amberol offers own range of planters and bins and limited moulding services. In recent years, Amberol is focused on the prior while maintaining only a small number of existing moulding service customers. In addition to its unique and patented ‘*Aquafeed*’ (self-watering) feature in its planter products, Amberol offers a range of customisable options. This includes a range of 16 colours to choose from, and option for customers to personalise the products through mould-in graphics, crest or plaque.

Make-to-Order (MTO) has always been the production strategy adopted by Amberol. This is mainly due to the customisable option of the products, and the intention of the company to reduce wastages in inventory and storage space. As the demand for planters is seasonal (highest demand from spring till mid of summer), Make-To-Stock (MTS) has been trialled to increase responsiveness of factory during peak season through buffer inventory. Since year 2015, a few historically popular and smaller size products have been selected for the trial. Although this has been trialled, Amberol is cautious of not to over-produced. Instead of using MTS to keep machines busy during off-peak, the company prefers to utilise available resources to expand its market share in bins through MTO.

In addition to the customisable options offered, Amberol also distinguishes itself by accepting low order quantity. The order quantity varies from a single unit to a hundred unit. From the 2015 data, the distribution is heavily skewed towards small order quantity with close to 70% below 10 units and 5% above fifty units. A typical distribution of order quantity is shown in *Figure 2.3* using data in year 2015.

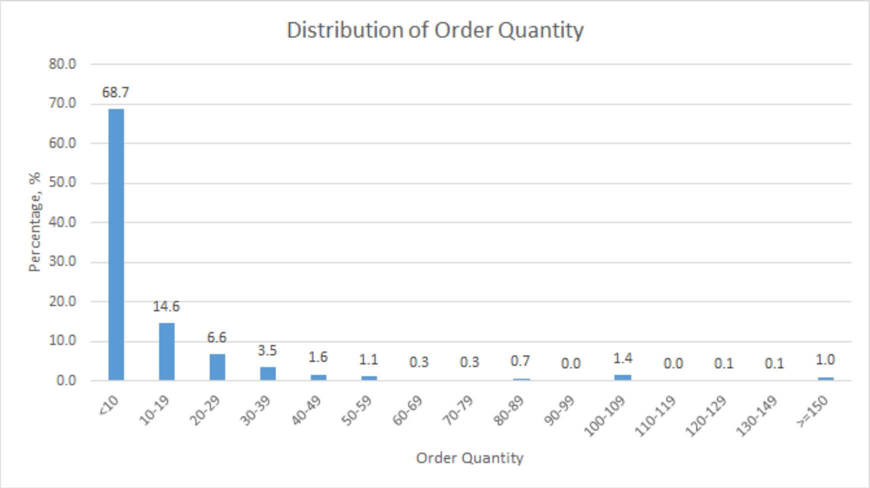


Figure 2.3: Distribution of Order Quantity (2015)

Due to the marketing and production strategy adopted, all resources are heavily shared with no dedicated production line. However, there is a dominant production flow as shown in *Figure 2.4*. The manufacturing process starts with *Moulding*, followed by *Trimming*, *Assembly*, *Finishing*, and finally *Packaging*. These processes are grouped and performed by two departments. The *Moulding* and *Trimming* processes are performed by *Moulding department*, whereas *Assembly*, *Finishing*, and *Packaging* are completed by *Finishing department*. These processes are manual and labour intensive. The process flow is as shown in *Figure 2.4*. Each process is briefly illustrated.

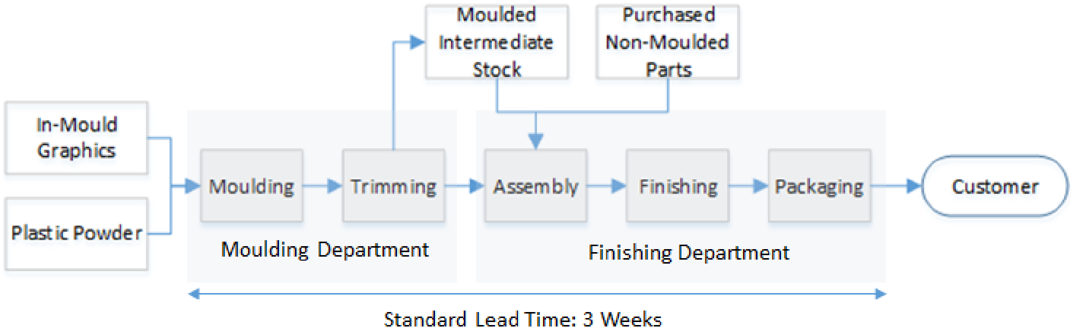


Figure 2.4: Typical Manufacturing Process Flow in Amberol

Moulding

Moulds required are transported using a forklift from the mould storage area to the designated machine load/unload area. Moulds are lifted and mounted onto the intended position on the machine’s arm either by hand or with the help of the installed crane. Illustration of a moulding machine is shown in *Figure 2.5*. Once a mould has been securely mounted, in-mould graphic is affixed before going through the four main moulding stages as illustrated in section 1.2.1.

The manual removal of moulded items from their mould requires experience and trained skills so as not to damage either the product or the mould. The moulded items vary in sizes, taking planters as example, typical small planter has a dimension of 0.47m in diameter, 0.24m in depth and 5 kg in weight, whereas a typical large planter has diameter of 1.5m, depth of 1m, and weight up to 50 kg. Larger products require more than one person to demould.

Upon demoulding, certain products require special attention before reaching room temperature. These products are placed into a *jig* with air being blown into the hollow part of the product to avoid surface deform due to temperature drop. Before the mould is used for the next moulding cycle, it needs to be manually cleaned to avoid stains on the next moulded product.

Aside from the raw materials (mainly plastic powder or resin and in-mould graphics) and human labour, moulds and machine spaces are critical resources in moulding. Both moulds and machine spaces are finite resources, costly to acquire. For moulding process to be successful, both mould and machine must form a *match* according to their inherited properties.

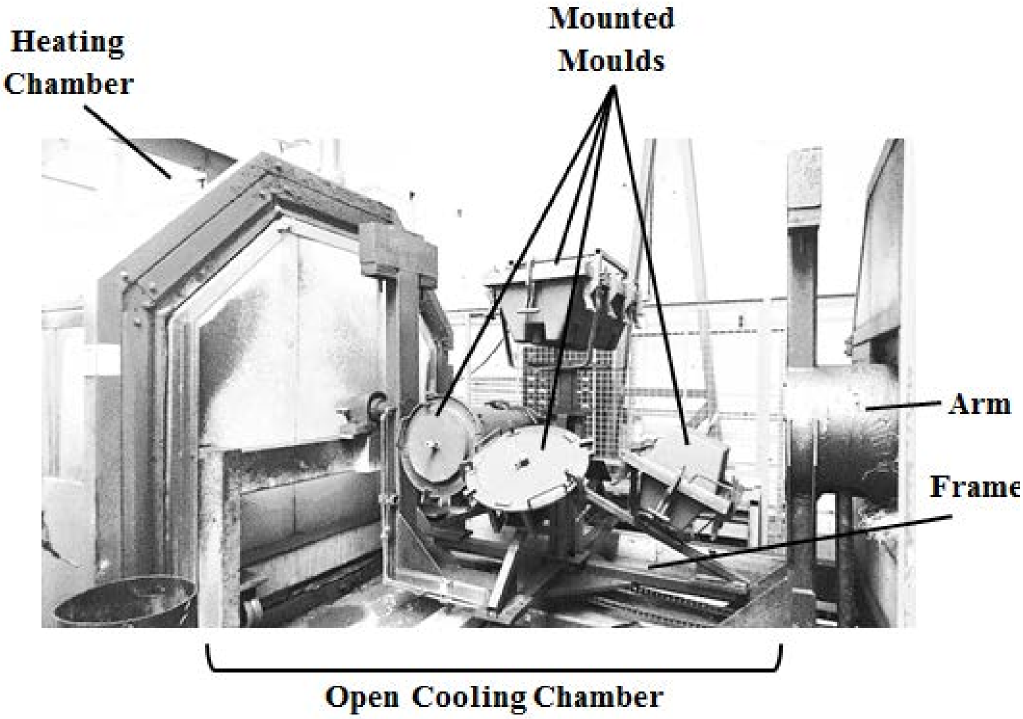


Figure 2.5: Moulding Machine

Physical properties include the size and weight of loading, as well as the heating and cooling properties. For example, each machine takes different time to arrive at a desired temperature in the heating process due to different model and age of the machine. For cooling process, each machine has own cooling properties due to different cooling methods and cooling chamber design. Machines with concealed cooling chamber has a relatively ‘controlled’ cooling profile. Machines with open cooling chamber are more sensitive towards changes in ambient temperature. This includes longer cooling time in summer, and shorter time in winter.

The moulding process is also dependant on the mould design. Due to different heat transfer properties exhibited by different materials, the materials used to construct the moulds directly affect heating and cooling time. The design of the mould also directly affects the moulding process. Moulds with multiple removable parts increases the mould setup time and requires additional post-moulding steps. Some moulds, due to different material used and unique design, requires additional manual pre-heating process before entering oven.

Based on the highlighted characteristics of mould and machine discussed above, a *match* must be formed in the mould-machine set up process. This *matching* can be summarised according to the following factors: process time, physical requirement, capacity and practicality.

(i) Process Time

Each product, due to the amount of powder, type of powder and mould design, has its own heating and cooling time. For example, product X requires 40 minutes of heating and 60 minutes of cooling, whereas product Y requires only 7 minutes of heating and 10 minutes of cooling. Over-heating will degrade its quality, resulting 'brittleness' which reduces its impact strength. Under-heating will result in bubbles formed in the product due to half molten plastic powder. 'Matching' the heating and cooling profile of both product and machine will determine the number of cycle or production throughput per shift.

Apart from the heating and cooling profile, process time is also determined by the number of moulds mounted on a machine. As the complete moulding process includes loading of raw materials and unloading moulded products from a mould (which will be referred to as *setup/demould*), the increase in number of moulds will directly increase the overall process time of product. The total moulding process time, T_m, for *n* number of moulds can be represented by equation (2.1).

$$T_m = (t_h + t_c) + \sum_{i=0}^{n} t_{si} \qquad (2.1)$$

where i is the number moulds; t_{si} is the setup/demould time for mould i; t_h is the heating time; t_c is the cooling time.

The relationship between moulding throughput, *M*, expressed in terms of total moulding process time, T_m, can be expressed using equation (2.2).

$$M = \frac{h \times N}{T_m} \times n \qquad (2.2)$$

where h is the number of minutes per shift, N is the number of shifts, and n is the number of moulds. From equation (2.2), Moulding throughput can be increased by the increase in buffer capacity through the increase in number of shifts or the increase of number of moulds mounted to a machine. Noticing that number of moulds is in the function of total moulding time, T_m, the increase in mould numbers will also decrease moulding throughput.

(ii) Physical Requirement

In Amberol, the rotary moulding machines have either two or three arms. All machines rotate in biaxial rotation, which makes full rotation in two axes. To ensure molten plastic flows and form even thickness coats on the inside of the mould, it is necessary to ensure the arm of machine rotates at a slow and constant rotation speed. For this, it is necessary for the loaded arm to be balanced in weight both vertically and horizontally. This is particularly important if more than one mould is mounted on an arm as illustrated in *Figure 2.6*. If mould on position 1 in *Figure 2.6* is too heavy, a counter weight balance must be mounted at the bottom of the

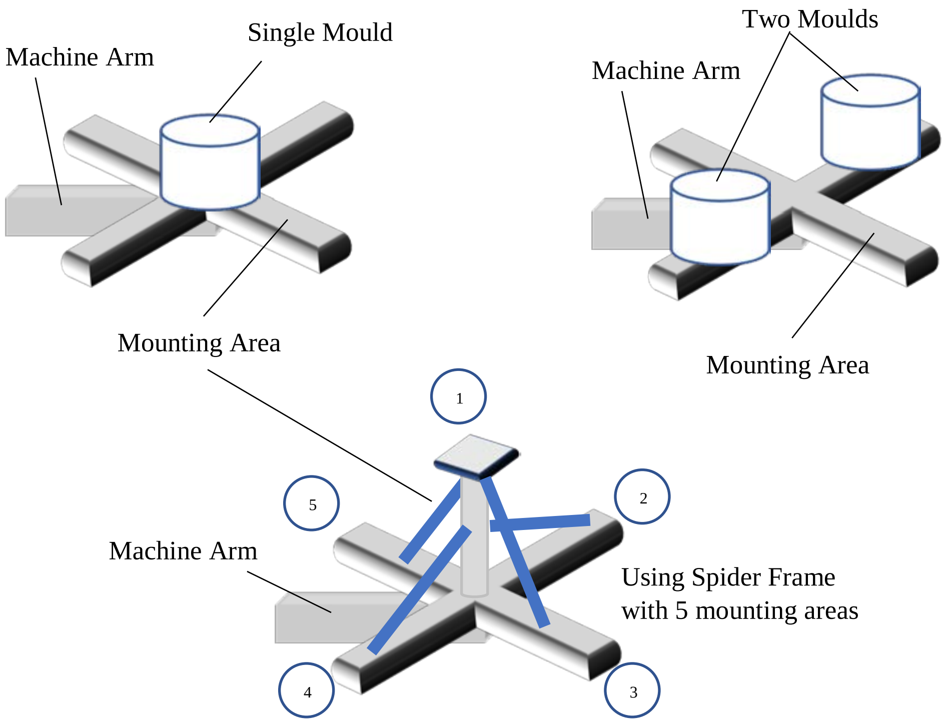


Figure 2.6: Physical Requirements on Machine Arms

arm. In addition, each machine arm has a limit in the weight it could carry. Overloading will potentially reduce the lifespan of mechanical parts such as motors and gears. It may also cause *cracks* on arms.

The second physical consideration is mould dimension and clearance to load raw materials and unload moulded product. Over a span of two to three decades, moulds used in Amberol have been designed with a lack of consideration on the overall production process. For example, the design of non-standardised mounting frames, lid position and type of lid clamps. Problems are most apparent on machine arms which are fitted with *spider frame*. This is a frame designed to increase the total number of moulds mounted on an arm, as shown in *Figure 2.6*. However, the non-standardised design of moulds added additional complication in mounting moulds on the same frame. For example, position 2 and 3 have limited lid clearance available compared to position 3 and 5.

To fully utilise available arm/frame spaces during busy period, various manual interventions are required. This includes extending frame height, changing mounting plate, changing arm frame or the more extreme means such as welding. Due to the limitation of heating chamber, minimum overall clearance has to be maintained for all three dimensions (height, width and length) of a fully loaded machine arm. This becomes more complicated as every machine has different arm loading and clearance requirement, leading to the next consideration: capacity.

(iii) Capacity

Resource capacity plays a role in determining the best machine-mould match. In moulding, with both machine and mould being the *limited* resources, the decision in resource deployment has direct impact to the overall system production throughput (as discussed in (i) process time, equation (2.2)). For example, product X, given its production process requirement has n number of machines mounting possibilities. This can also be known as parallel machine routing options (*Figure 2.7*). If there are m number of moulds available, the total number of routing options becomes the multiplication of m and n.

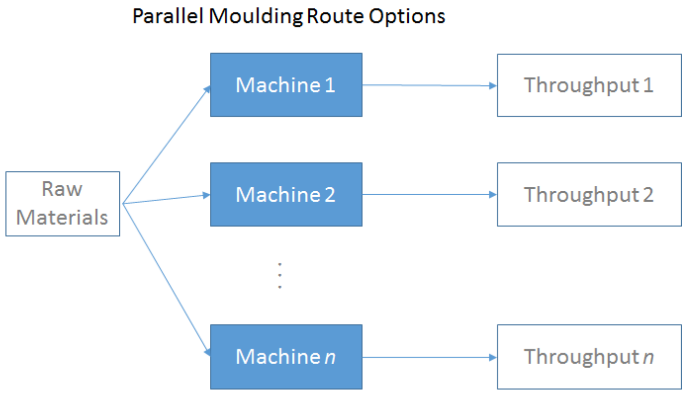


Figure 2.7: Parallel Moulding Route Options

The number of parallel machine routing option is dependent on the two factors discussed: (i) Process Time and (ii) Physical Requirement. Typically, smaller moulds have larger number of options. Although placing factor (i), (ii) and (iii) together increases complexity, the parallel moulding route options and availability of additional moulds can be functioned into various buffer capacity options. The use of *time* to increase buffer capacity by increasing number of shifts has been discussed under factor (i) Process Time.

(iv) Practicality

This factor is highlighted to capture the *trial and error* and *pragmatism* nature adopted by the shop floor in the moulding process. In theory, rotational moulding process is a relatively simple process and expects less variabilities and uncertainties. However, every moulding machine operator acknowledges the existence of *variabilities and uncertainties* in the process. This is evident by the frequently used phrase: '… *it all depends…*', on the shop floor. Many practices, throughout the years, particularly in arriving at the *best machine-mould* match through experience has been passed on from seniors to juniors.

Due to limitation in available resources (such as financial, expertise and equipment), although unwanted phenomena have not been formally researched and documented, arriving at a pragmatic solution through trial and error is what matters. For example, a mould is often placed onto certain machine arm or at certain position because it shows least quality problems through experience. Another example is in the event where there are orders for multiple colours of similar product, sequencing the production according to colour may avoid spending additional resources to clean the mould.

The various factors discussed above forces shop floor personnel to adhere by last known best practices to keep things going. Upon completing the moulding stage, moulded products are progressed to the trimming stage.

Trimming/Cutting

This step is important to smoothen parting lines formed between mould pieces. It is also needed to smoothen any edges. Normally, this step is easier to be completed before the temperature of moulded product drops to room temperature. Cutting is also perform at this stage for products which are difficult to be cut after it returns to room temperature.

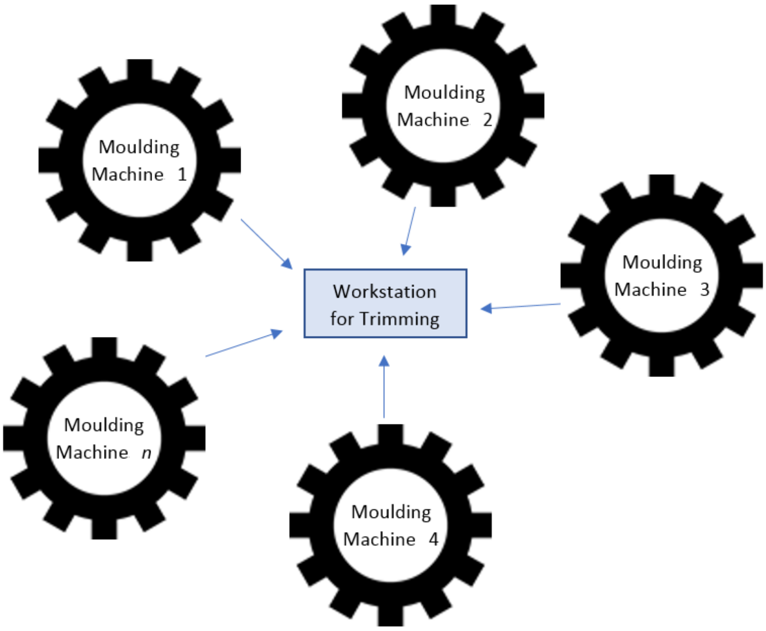


Figure 2.8: Shop Floor Layout in Amberol

Through years of experience, the layout of shop floor has been improved with the trimming workstation becoming an island surrounded by moulding machines. This is to facilitate coordination and smooth product flow between moulding machines and trimming workstation, as illustrated in *Figure 2.8*. Without needing formal documentation given to ‘trimming’ workstation, there is informal understanding for production manager to space out moulded products which requires additional trimming and cutting. Machine operators equipped with trimming and cutting skills will render support to trimming process if necessary. This is possible as there is a *waiting* time in between machine runs.

In addition to the task of trimming and cutting, quality control (QC) related activities are also conducted in this stage. While trimming, the personnel inspects the product for any defects such as surface unevenness (or inconsistent wall thickness), powder contamination or existence of visible bubbles formed on product wall. The '*island*' layout allows feedback to be made known to respective machine operators for process refinement. Non-defect products are labelled with a QC sticker (with personnel initial and date) before proceeding to the next stage: Assembly/Finishing.

Assembly/Finishing

This stage is product dependent, where products composed of multiple moulded or/and non-moulded components will require the assembly stage before proceeding to finishing stage. For certain products, assembly and finishing are not a unidirectional process. Rather, it involves multiple visits of both processes before a product is ready to be packaged. For example, a bin is made up of fifteen moulded and twenty non-moulded components. As all assembly/finishing works are done manually, skills and craftsmanship directly impact the actual processing time. Amberol has adopted multi-skill strategy for assembly/finishing, where every personnel in this department is trained and equipped with skills to work on multi products. This enables flexibility in resource allocation. In this stage, personnel perform the final QC. This includes inspection of the final product assembly, which is consists of both moulded and non-moulded parts.

With the understanding on the manufacturing process, section 2.2.3 continues to illustrate how manufacturing process fits into the overall business process, particularly between manufacturing and non-manufacturing department.

2.5 Challenges and Issues Identified in Amberol

The challenges and issues identified in the business process is summarised in *Table 2.2*. This summary groups the challenges into three broad categories: *Pre-Sales*, *Post-Sales* and *Others*. In search for a solution to address the challenges identified in Amberol's manufacturing environment, a KTP project was approved where Amberol seeks to deploy a TOC based production planning and control (PPC) system in MTO environment. The next chapter will review the appropriate PPC applications advocated in this environment.

Table 2.2: Summary of Challenges and Issues in Amberol's Business Process

	Standard Practice	Description	Undesired Effects (UDEs)
Pre-Sales	Customer Enquiry Stage: • Standard industrial lead time is quoted • Exceptional cases such as large quantity or with customised features will be discussed between shop floor, sales/marketing, and purchasing before deciding on a most probable delivery date (often based on experience)	• As management's attention is only triggered on exceptional cases, this causes accumulation of small quantity orders on similar products by different customers to evade management's attention. For example, an order of hundred units will immediately catches the management's attention, but not twenty-five orders of four units. • Some of the products, though being named differently, uses similar resources on the shop floor, for example the mould. Other than causing unrealistic due date to be quoted, it also causes the emergence of critical capacity resources (CCR).	• Unrealistic due date quoted • Causing critical capacity resources (CCR) to form unknowingly • Too late for management to response
Post-Sales	• Similar products are being accumulated and produced, reducing setup time • Office will only be notified upon work order completion • A practice where each work centre will work towards the 'shop floor accepted production time'.	• All production related matters are decided by production manager • The production manager has been managing well with tacit knowledge amassed throughout the years. However, the process is manual, providing no visibility to others. • 'Shop floor accepted production time' adopted in each department has 'buffer time' allocated to them individually. Parkinson's Law exist where jobs tend to automatically 'spread' to consume the buffer time unnecessarily. This often cause job priority to be masked.	• Missed due date • Hidden capacity resources • Not able to deploy buffer capacity in time • Buffer time is wasted • Reactive and fire-fighting production management • Manufacturing related Information is withheld only by PM.

	Standard Practice	Description	Undesired Effects (UDEs)
Others			• Issue of succession and knowledge dissemination • Out-dated BOM record. • Inaccurate/ delayed manufacturing related data dissemination • Troublesome to retrieve order status/progress. • Information captured and recorded in ‘silos’. • As word order status is only known by production manager, there is tension and discord between sales personnel and production team. As a result, requiring daily intervention by senior management.

Chapter 3: Literature Review

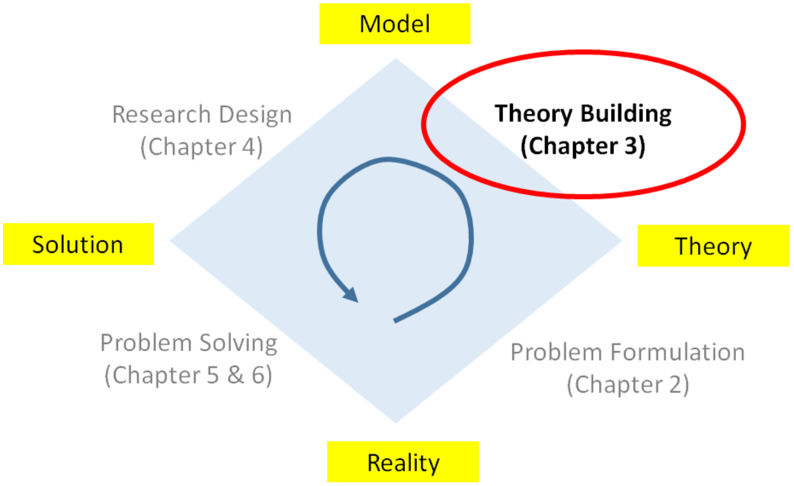


Figure 3.1: Organisation of this Thesis

Source: Adapted from Van der Ven (2007:10)

In previous chapter, it is understood that the senior management of the company intends to deploy a TOC based PPC application to solve its manufacturing related issues and challenges. Acknowledging the importance of *fit* between *contextual environment* and *best practice*, the following research questions have been formulated:

RQ1: ***What are the concepts underpinning S-DBR and how can they be configured to meet specific MTO contextual environments?***

RQ2: ***What are the implementation issues in S-DBR and how may they be addressed?***

To answer these research questions, a company diagnostic was conducted and described in previous chapter. At the end of the chapter, the issues and challenges faced in the company are highlighted.

This chapter continues to explore these research questions by conducting a critical review on relevant literatures. The first half of this chapter will use theoretical arguments to answer RQ1. It begins by providing a review on appropriate PPC applications in MTO environment. This review shows that TOC based PPC application is deemed inappropriate. Instead, Workload Control (WLC) is advocated as the most appropriate PPC application in such environment. This contradicts with the perspective of practitioners in Theory of Constraints International Certification Organisation (TOCICO).

This warrants a critical review on both WLC and TOC based PPC applications: Drum Buffer Rope (DBR) and Simplified Drum-Buffer-Rope (S-DBR). With the understanding of their underpinning concepts, the similarities and differences between the two will be explored. The appropriateness of S-DBR for generic MTO environment will be re-evaluated by adopting prior criteria used to evaluate WLC.

The second half of this chapter will focus on RQ2. This is done by reviewing the implementation issues identified in both WLC and S-DBR. At the end of this chapter, a conceptual framework will be constructed to underpin this research. The organisation of this chapter is described in *Figure 3.2*.

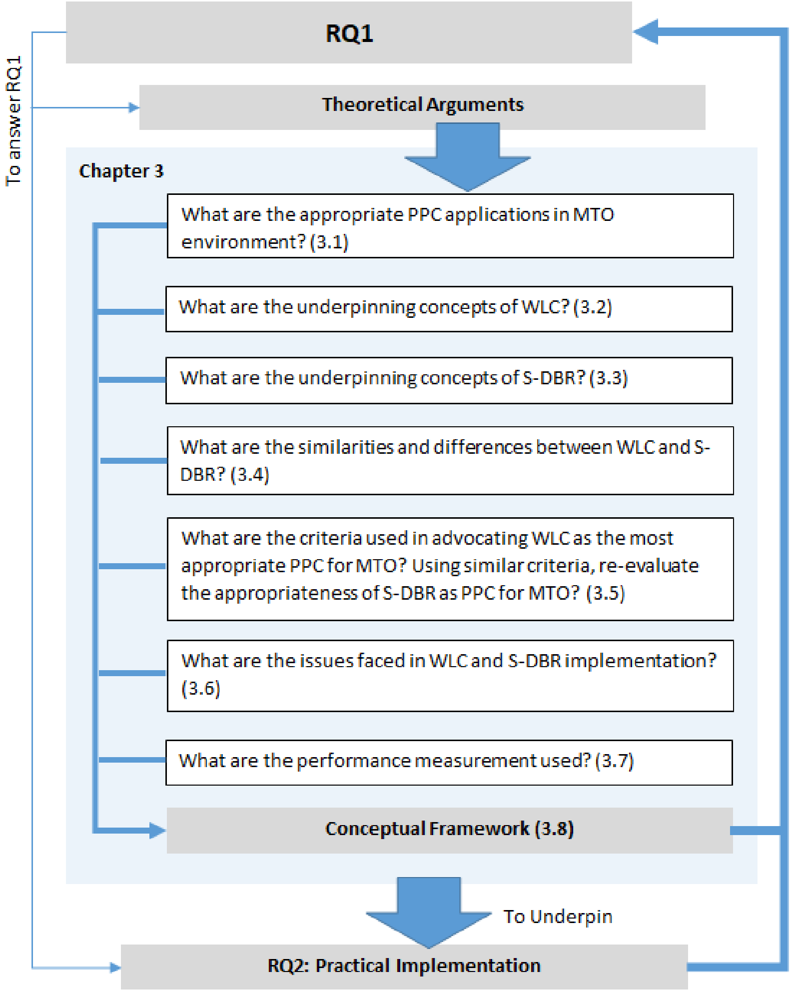


Figure 3.2: Organisation of Chapter 3

3.1 PPC in MTO Environment

Traditionally, manufacturers resort to make-to-stock (MTS) strategy to achieve optimal cost and production rate relationship, such as economic order quantity (EOQ) (Osteryoung et al., 1986). Inventory created via MTS is used to respond to market demand, avoiding shortages while providing buffer time for supply chain to respond and replenish stock. Driven by competition, manufacturing companies make strategic choice to offer product customisation to gain competitive advantage (Hendry and Kingsman, 1991; Amaro et al., 1999). This strategic choice brings forward order penetrating point (OPP) before the start of manufacturing (Olhager, 2003). This makes market demand forecast impractical in *Non-MTS* manufacturing environment.

Non-MTS includes Assemble-to-Order (ATO), Make-to-Order (MTO) and Engineer-to-Order (ETO) (Hendry and Kingsman, 1989; Wortmann, 1992). With the attempt to better represent the categories within *Non-MTS*, Amaro et al. (1999) suggested a new taxonomy. This new taxonomy represents *Non-MTS* categories in a spectrum according to level of customisation. One end of the spectrum is represented by *non-customisation* production, and on the other end, *pure design* which resembles *project* environment.

While acknowledging there are various definition available in literature, in this research, non-MTS will be broadly referred to as MTO (Hendry and Kingsman, 1989; Amaro et al., 1999; Stevenson et al., 2005). The definition of MTO will be adopted from the Operations Management Body of Knowledge (OMBOK) by the American Production and Inventory Control Society (APICS). MTO is refers to manufacturing environment where '*products are made entirely after the receipt of a customer order. The final product usually is a combination of standardised and custom items to meet the customer's specific needs*' (OMBOK, 2016). Other than MTS and MTO manufacturing environment, in Theory of Constraints (TOC), a hybrid environment of MTS and MTO known as the concept of MTA (Make-To-Availability) has also been introduced (Beemsterboer et al., 2016; Benavides and Van Landeghem, 2015; Schragenheim, 2010).

The strategic move from MTS to MTO poses different set of challenges to companies. In MTS, variation and uncertainties are mainly reduced by buffer inventory. In MTO, the challenge lies in the determination of feasible delivery date (DD) for orders. This requires the input of updated 'lead time' information which is dependent on the availability of capacity resources (Hendry and Kingsman, 1989; Ozdamar and Yazgac, 1999).

There are two types of DD: (i) the negotiable DD where DD is proposed or quoted by company, and (ii) fixed DD where DD is specified by customer (Thurer et al., 2017). PPC (Production planning and Control) is considered the *bridge* between production and marketing (Berglund and Guinery, 2008; Hendry and Kingsman, 1989; Parente, 1998). Thus, a PPC suitable for MTO should have the *Customer Enquiry* feature to assist company in handling the above DD types (Hendry and Kingsman, 1989; Stevenson et al., 2005).

Various approaches have been proposed to achieve this planning (scheduling) process. Scheduling approach has been grouped into three categories by researchers (Hendry and Kingsman, 1989; Wiers, 1997): (i) Optimal, (ii) Heuristic, and (iii) Artificial Intelligence. The first approach involves modelling shop floor using mathematical formulation. It includes simulation using algorithms which attempt to model uncertainties and produces detailed sequences. This approach has been criticised by researchers as impractical, over-simplification of real-life scenario (Hendry and Kingsman, 1989; Mula et al. 2006; Wiers, 1997).

The second approach involves introducing dispatching rules in the form of heuristic algorithm. Instead of producing a detailed sequence, dispatching rules are used only to determine the selection of next work order to be processed. Researchers express doubt that these dispatching rules perform better than existing shop floor personnel (Arica et al., 2014; Hendry and Kingsman, 1989). It is argued that shop floor personnel can handle much more complex situations than the written dispatching rules. As dispatching rules and their underlying assumptions are contextual, their success might not be generalizable.

This has led to the attempt to develop artificial intelligent systems with complex algorithms which is able to capture all dispatching rules used by shop floor personnel. This is deemed impractical due to the dynamic nature of MTO manufacturing environment, where shop floor personnel are always *learning* and *changing*. This requires *new knowledge* to be continuously *learnt* by the planning system. Such complex system will be impractical for SMEs to maintain.

A major challenge to PPC lies in the generation of practical production plans. This practicality refers to feasibility in the *execution* part of the PPC, to fulfil the due date promised to customers in the *planning* (Schragenheim, 2010:213; Wiendahl et al. 2005). While it is a challenge to provide customers with a reliable due date, it is a different challenge to fulfil them. Impractical due date in *planning* will cause *execution* to fail in fulfilling them. Repeated failures in *execution* will result in PPC being perceived as a defunct system, forcing longer lead time to be quoted. In return, the increased lead time will both mask resource capacity and hide production related issues.

The misalignment between *planning* and *execution* is described as a stumbling block in PPC implementation (Wiendahl et al., 2005). This misalignment is due to the different perspectives on *planning* (Fransoo and Wiers, 2006; McKay and Wiers, 1999; Romero-Silva et al., 2015). The classical concept views *planning* as mere mathematical problem, *static* in nature. In addition, the mathematical solution assumes supply (upstream), demand (downstream) and manufacturing related resources to be static (Wiers, 1997; Karltun and Berglund, 2010). This approach is detailed by researchers such as Pinedo (2008) and Deblaere et al. (2007).

Acknowledging the dynamic nature of *planning*, the second concept view *planning* as *reactive*. This involves the constant updates in *planning* based on the *feedback* received from *execution*. As highlighted by Arica et al. (2016), in practice, planners spent most of their efforts reacting continuously to unforeseen circumstances. The dynamics involved in such decision-making process are contextual, event driven, and necessitate in-time intervention. Instead of relying on complicated yet impractical mathematical dependant approach, practitioners in operations management have introduced practical PPC solutions to both plan and control (McKay et al., 2002; Tenhiala, 2011; Wiers, 1997).

As highlighted by Bonney (2000), in BS 5192 (Guide to Production Control by British Standard), it acknowledges the tendency for PPC designers to counter complex operations with complex PPC solutions. Thus, the guide cautions against over-complicating PPC solutions, and seek to arrive at simplified and practical solutions. Some classic PPC systems are such as Ford system by Ford, Toyota Production System (TPS) by Ohno, and Theory of Constraints (TOC) by Goldratt. In all three approaches above, mechanism is used to control the production flow. In Ford system, *space* is used to limit over-production. In TPS, *inventory* is used; whereas in TOC, *time* is used. Associate with each mechanism above is a practical signalling system used to align *planning* and *execution*. In Ford, *Direct Observation* is used; in TPS, *Kanban* is used; whereas in TOC, *Buffer Management* is used (Goldratt, 2009).

Although the above practitioner-led PPC approaches have been successful, reviews by researchers such as Hendry and Kingsman (1989) and Stevenson et al. (2005) argued against the suitability of the above approaches in the dynamic MTO manufacturing environment. Instead, researchers advocate the use of input/output control concept to realise *planning and control* in MTO environment (Bechte, 1988; Hendry and Kingsman, 1989; Tatsiopoulos and Kingsman, 1983; Wight, 1970). This concept has been further developed and is known as workload control (WLC) (Land and Gaalman, 1996; Thurer et al., 2011).

While researcher-led WLC is being developed, the practitioner-led TOC has also explored new development on its PPC application for MTO environment. Based on its TOC application for manufacturing: DBR (Drum-Buffer-Rope), an MTO PPC known as S-DBR (Simplified Drum-Buffer-Rope) is introduced (Schragenheim and Dettmer, 2000).

Reviews on DBR by academic researchers have regarded DBR as a non-suitable PPC application for SMEs in MTO environment (Hendry and Kingsman, 1989; Stevenson et al., 2005). This seems to contradict the implementation of TOC based MTO application advocated by TOCICO practitioners (Theory of Constraints International Certification Organisation). For WLC, although it has been advocated as the most appropriate PPC application in MTO, its proliferation among practitioners seems limited (Stevenson et al., 2005; Hendry et al., 2008; Thurer et al., 2011; Silva et al., 2015).

Noticing the academic and practitioner gap between WLC and TOC based PPC applications, this chapter attempts to explore and bridge this gap.

3.2 Workload Control (WLC)

WLC originates from the idea of input-output control in as early as the 70s (Wight, 1970). Under this concept, job input into the production system has to be controlled and limited according to the production output capability. As described by Land and Gaalman (1996), the paradigm introduced by WLC is to conceptualise job shops as queueing system. Queue length is controlled through various control points. By adopting hierarchical production control concept, WLC focuses on three control points: 'job entry', 'job release', and 'priority dispatching', as shown in *Figure 3.3* (Gelders and Van Wassenhove, 1982; Kingsman et al., 1989; Land and Gaalman, 1996).

In hierarchical approach, organisational decisions are made based on length of planning horizon. Context is subsequently set by the higher-level plan in which the next level plan operates. In a typical PPC, the details in planning increases from a higher level to a lower level (Bonney, 2000). This suggests necessary detailed planning for shorter planning horizons. As decision making at each level varies according to its focus and consideration, the information required and associated in each level varies accordingly. In practice, the 'title' and 'role' of a personnel might not be designated according to the distinct hierarchical level (McKay and Wiers, 2006). Conceptually, it highlights the importance of 'time' factor on each level.

In WLC, the 'job entry' level is the highest level in the hierarchy, enabling medium term production planning. This is followed by the 'job release' level, which is for short term. The lowest level is the 'priority dispatching' level, which deals with day-to-day

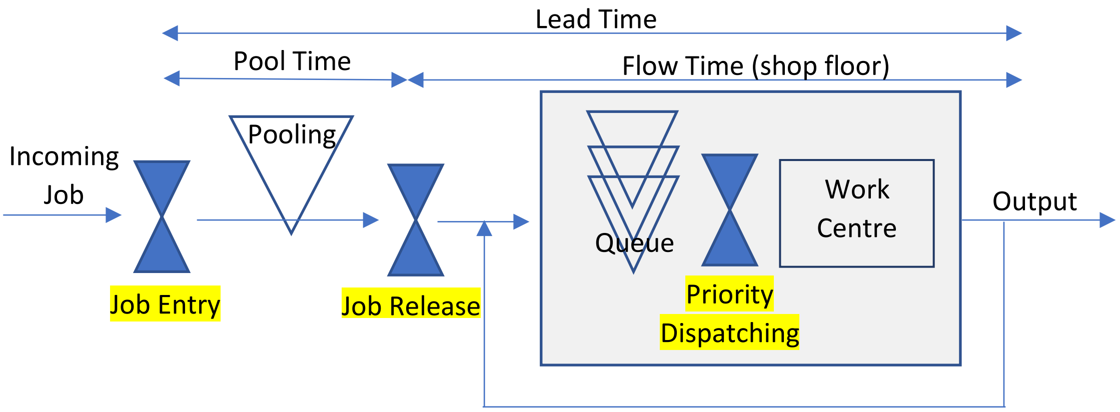


Figure 3.3: Three Control Points in WLC
Source: Adapted from Land and Gaalman, 1996

shop floor planning and control (Kingsman and Hendry, 2002; Kingsman et al., 1989). Control at each control point is realised through various control mechanisms. Jobs accepted are controlled through 'release decision', which is also known as order release mechanism (ORM) (Bergamiaschi et al., 1997; Sabuncuoglu and Karapinar, 1999). Once on the shop floor, work load is progressed through work centres via priority dispatching (Kingsman 2000; Land et al., 2014).

Over the years, the simple IOC concept has been further researched and developed into WLC (Land and Gaalman, 1996). Various rules have been researched and introduced to support the 'release decisions' around the three control points. The objective is to reduce lead time and work-in-process (WIP), and increase throughput and due date performance (DDP). In addition, buffers are introduced to protect production system against variabilities and uncertainties (Thurer et al., 2012). These rules have been categorised and discussed from various perspectives by Bergamiaschi et al. (1997), Fredendall et al. (2010), Henrich et al. (2004), Sabuncuoglu and Karapinar (1999) and Thurer et al. (2012). Other than WLC, JIT and Drum-Buffer-Rope (DBR) in TOC are reviewed as fundamentally adhering to the IOC concept (Fry, 1990).

A detailed review on the development of WLC (from 1980 to 2009) shows that WLC introduced by Lancaster University Management School (LUMS) is the main theoretical approach adopted post-2000 (Thurer et al., 2011). In addition, its latest LUMS Corrected Order Release (COR) has been advocated as the best order release solution (Thurer et al., 2012; 2016). Other than the *traditional* three-tiered hierarchical WLC approach, LUMS approach included an additional 'customer enquiry' stage to provide a decision support system (DSS) for companies (Hendry and Kingsman, 1991; Stevenson, 2006). Although there have been a significant increase in the WLC related research, a post-2010 review by Romero-Silva et al (2015) shows limited report on successful WLC implementation in industry, with only one practitioner led intervention.

The remainder of section 3.2 will review WLC from the perspective of the four hierarchical planning stages introduced by LUMS: Customer Enquiry, Job Entry, Job Release, and Priority Dispatch (Huang, 2017; Stevenson 2006a). In this review, the conceptual differences between the three major strands found in WLC will also be discussed. The mathematical perspective on WLC has been detailed in works by Kingsman (2000), Land (2006), Stevenson (2006a) and Thurer et al. (2017a).

3.2.1 Customer Enquiry Stage

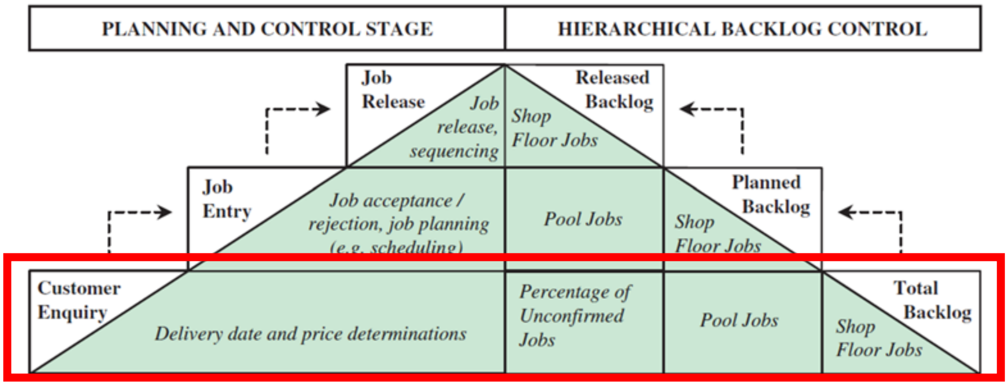


Figure 3.4: Customer Enquiry Stage in Hierarchical Backlog Control Framework
Source: Stevenson and Hendry, 2006

The importance of 'DD determination' to MTO companies has prompted researchers to include it as part of WLC concept (Bertrand, 1983; Ragatz and Mabert, 1984; Hendry and Kingsman, 1989). LUMS approach has explicitly added 'customer enquiry stage' as part of its DSS design (Hendry and Kingsman, 1993; Kingsman et al. 1996; Kingsman, 2000; Kingsman and Hendry, 2002; Stevenson, 2006a). The purpose of this stage is to provide customer with DD at quotation stage, engaging customers into the PPC at an earlier stage, before order confirmation.

There are two scenarios under which DD is set: (i) Negotiable, where DD is proposed by the manufacturing company, or (ii) reasonably fixed, where DD is specified by the customer (Thurer et al., 2017a). Total backlog of work is used as a reference to determine feasible DD. The backlog of work in this stage divided by the capacity is known as 'total backlog length' (TBL). The backlog length of work is controlled over a *planning horizon*: a limited time period, where backlog length of work should not exceed the *planning horizon*.

As highlighted by Kingsman and Hendry (2002), the main underlying concept of LUMS WLC approach is to manage the total amount of work in system so that it is completed within the *planning horizon*. Thus, the following parameters are necessary to be pre-determined by the management before the implementation of WLC (Hendry et al., 1998):

(i) The length of planning horizon: This is effectively the maximum allowed backlog length which is also the maximum lead time.

(ii) The maximum LT for small orders: This is to prevent using maximum LT of *large* orders on *small* orders.

(iii) Threshold for *small* and *large* orders.

The backlog length and lead time in each corresponding WLC hierarchical stage is illustrated in *Figure 3.5* below.

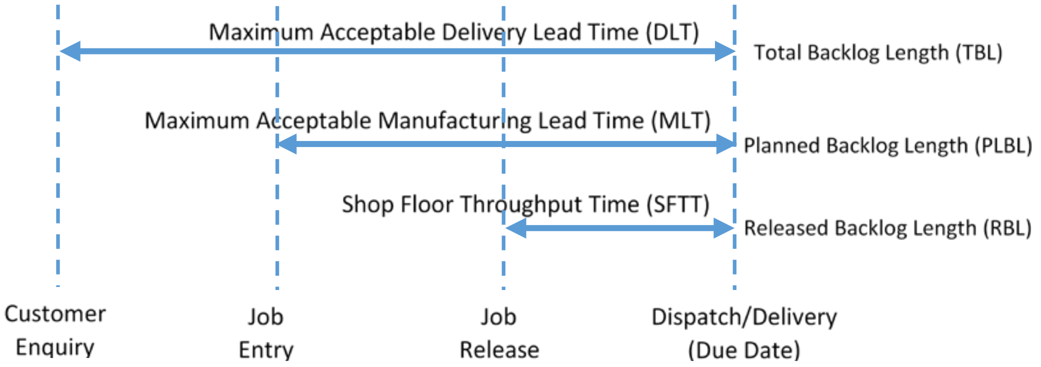


Figure 3.5: Lead Time and Backlog Length in WLC

Source: Adapted from Stevenson (2006)

Total backlog or also known as *total workload (TW)* is determined by totalling both future and existing confirmed and unconfirmed jobs in time unit. TW considers both processing time and setup time required at each work centre. Unconfirmed jobs are further incorporated with a *success strike rate* factor, which is company dependant. Based on TW, DD is determined by adding the total processing time required by the enquired job onto necessary work centres. If the necessary lead time exceeds the requested DD, a new DD is proposed. The equation to determine TWC (Total Work Content) and TB (Total Backlog) is shown as follows (Stevenson, 2006a):

$$TWC_i = \sum_{w=1}^{W}[(Q_i \times PT_{iw}) + ST_{iw}] \qquad 3.1$$

where *i* is a job with with DD ≥ *d*; TWC_i is total work content of job *i*; Q_i is the quantity of job *i*; PT_{iw} is the unit processing time of job *i* at work centre *w*; ST_{iw} is the setup time of job *i* at work centre *w*.

$$TB_d = \sum_{i=1}^{I}[SR \times TWC_i] + \sum_{j=1}^{J} TWC_j \qquad 3.2$$

where SR is the overall strike rate of the company; TWC_i is the total work content of unconfirmed job i with $DD \geq d$; TWC_j is the total work content of confirmed job j with $DD \geq d$. TBL is determined considering the daily capacity of work centre.

3.2.2 Job Entry Stage

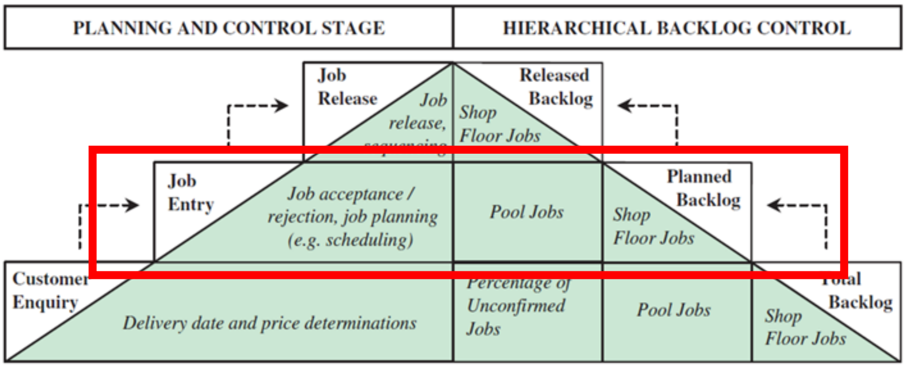


Figure 3.6: Job Entry Stage in Hierarchical Backlog Control Framework
Source: Stevenson and Hendry, 2006

In this stage, customer returns to company with a confirmed order. Before accepting the order with the specified DD, the feasibility of meeting the DD is re-evaluated. The originally quoted DD might not be feasible as system loading might have changed. In addition, the orders in quotation might have been amended to reflect actual customer order. Upon feasibility check, jobs are either accepted, rejected or to renegotiate DD. The accepted jobs are placed in a ‘pool’. Although it is acknowledged that control at job release stage is able to reduce WIP and lead time (Tatsiopoulos, 1997), extending production planning and control into ‘pre-sales’ through both customer enquiry and job entry stages are particularly critical to MTO companies. As MTO environment is susceptible to higher variation and uncertainties from market enquiry and demand, these stages stabilise lead time and provides feasible DD by considering both workloads and capacities (Bertrand and Van Ooihen, 2002; Stevenson and Hendry, 2006).

Referring to *Figure* 3.6, *Planned Backlog (PLB)* is determined by considering only confirmed jobs. By using daily available capacities, *Operation Completion Dates (OCD)*, *Earliest Release Dates (ERD)* and *Latest Release Dates (LRD)* are able to be derived through backward scheduling from the DD. This information is needed to facilitate the monitoring of DD adherence. The availability of work centres between current date and DD is taken into consideration. The workload of new order is added to the planned backlog via the following equation (Stevenson, 2006a):

$$PLB_{wd} = \sum_{i=1}^{I}[(Q_i \times PT_{iw}) + ST_{iw}] \qquad 3.3$$

where i is a confirmed job with corresponding OCD ≥ d; Q_i is the quantity of confirmed job i; PT_{iw} is the unit processing time for confirmed job i at work centre w; ST_{iw} is the setup time time for confirmed job i at work centre w. The PLBL (Planned Backlog Length) is determined through similar way as TBL.

3.2.3 Job Release Stage

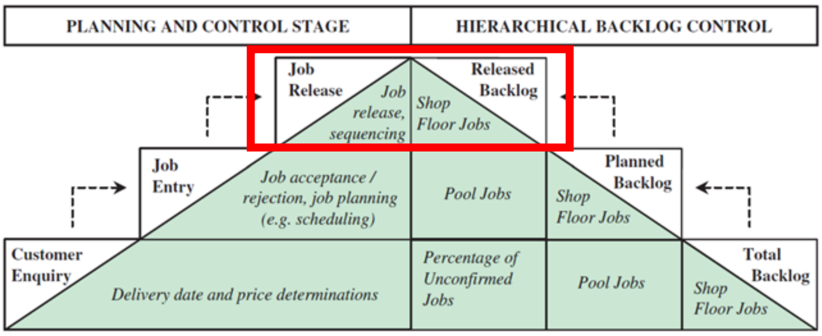


Figure 3.7: Job Release Stage in Hierarchical Backlog Control Framework
Source: Stevenson and Hendry, 2006

The jobs accepted into the system in the job entry stage is being placed in a *pre-shop pool*. A release mechanism is designed to control and manage the *flow* of jobs onto the shop floor. It is desirable in WLC to maintain a *stable* flow of jobs at each work centre (Oosterman et al., 2000). In addition, as highlighted by Melnyk and Ragatz (1989), effective shop floor control is achieved by controlling the *release* of jobs onto the shop floor rather than after. This essential part of WLC concept explicitly control WIP on shop floor by controlling the *queue* in front of each work centre, which is determined by the ‘workload definition’ and ‘workload norm’.

There are three major strands of WLC based on how workload is determined: (i) Bechte (1982, 1988), (ii) Bertrand (1981) and (iii) Tatsiopoulos (1983). In the review by Land and Gaalman (1998) and Thurer et al. (2011), these three major strands are classified into probabilistic and aggregate approaches. The probabilistic approach refers to the first WLC strand: Load-Oriented Manufacturing Control (LOMC), mainly developed at Hanover University in Germany (Bechte, 1994; Wiendahl, 1995). The latter two strands are classified as aggregate approaches, developed in Eindhoven and Lancaster. The later, known as LUMS WLC receives main attention from researchers post 2000 (Thurer et al., 2011). A detailed review, together with their underlying assumptions has been conducted by Breithaupt et al., 2002, Kingsman (2000), Land and Gaalman (1996), Land (2006) and Oosterman et al. (2000).

The key difference between the three major strands is the workload definition as shown in *Figure 3.8*. The workload considered by Bechte is the *queue length* at work centre, expressed in terms of processing time required and bounded by load limit of the work centre. The *queue length* considered consists of workload on hand (*direct load*) and a percentage (a probability factor) of upstream workload (*indirect load*), known as *converted load*. For cases where work centre is at gateway position, the converted load is the total workload on hand. In the process of converting upstream work load, the *position* of the work order at the point of conversion is taken in to consideration (as a multiplying factor). Work orders are firstly prioritised according to released date (*time limit*). This is determined by backward scheduling from job delivery date. Based on this priority list, the jobs are subjected to the workload norm at the work centre, which is a predefined load limit of a resource.

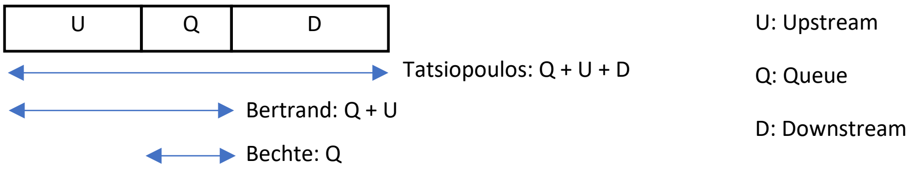


Figure 3.8: Workload definitions of three major WLC order release concepts
Source: Land and Gaalman (1996)

Although this method has been advocated for its suitability for pure job shops where there exist complicated routings, it has been criticised on its assumption used in estimating the probability of task completion at each station. With the assumption that jobs passing a work centre is only a fraction of the available processing time, jobs could be progressed whenever available time appears. For jobs with long processing time, the available time might not be sufficiently long enough to process them. By the end of the release period, only smaller jobs are *flowed* through. This reduces the accuracy of workload estimation (Land and Gaalman, 1996).

The workload considered by Bertrand differs by considering the total processing time of jobs yet to be processed by the work centre. This is known as *aggregate workload*.

As illustrated in *Figure 3.9*, the *aggregate workload* includes both work load on hand (*Direct Load*) and all work load upstream (*Indirect Load*). This release mechanism subjects the respective *aggregate workload* to the *workload norm* defined for each work centre irrespective of the routing of a job prior to arrival at each work centre.

The third major strand of WLC introduced by Tatsiopoulos considers *indirect load* by including processing time for both upstream and downstream, also known as *shop load* (refer to *Figure 3.9*). Workload of an order is only removed upon completing all processes on shop floor. Although this simplifies the need for progress feedback while moving in between work centres, it is not desirable as status of jobs are *hidden* (Oosterman et al., 2000). The jobs in the pool are prioritised based on shortest *slack time,* which is obtained by comparing current date with latest release date (LRD). Similar to other WLC release mechanism, the *shop load* is subjected to *workload norm* of each work centre.

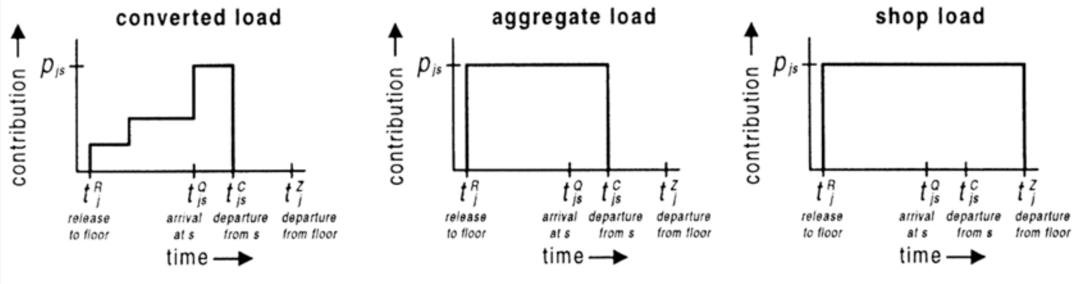


Figure 3.9: Workload of three major WLC order release concepts
Source: Oosterman et al. (2000)

Although aggregate load approach avoids the complexity of statistical estimation found in probabilistic approach, it is being criticised to have neglected the job position in the job routing. This is more apparent for aggregate load which considers both upstream and downstream. Work centres located towards the two ends of the work flow would risk being left idle due to job it has either long completed or job which is still a distance away before arrival. This results in inappropriate decision making in job acceptance and release (Land and Gaalman, 1996; Oosterman et al., 2000; Stevenson, 2006). Due to this concern, Oosterman et al. (2000) has suggested an improvement called *Corrected Aggregate Load* method. Based on the aggregate load concept by Bechte, the position of job at upstream is taken into consideration. This relative position is obtained through dividing the total upstream processing time by the number of work centres required in upstream routing.

Apart from the probabilistic and aggregate approach discussed, there is another approach which has recently regained the attention from researchers, known as the *bottleneck* approach (Enns and Costa, 2002; Fredendall et al., 2010; Thurer et al., 2017b). Drawing from Drum-Buffer-Rope (DBR) in Theory of Constraints (TOC) by Goldratt (1984), rather than controlling workload at all work centres, the *Bottleneck Load-Oriented* release mechanism concerns only the workload associated with bottleneck work centre. This assumes that the production output is determined by the bottleneck work centre. Further review regarding the mixed results obtained in the comparison studies between bottleneck and aggregate approach will be discussed in section 3.4.

Apart from *workload definition*, the other critical parameter in WLC release mechanism is *workload norm*. This is also known as *workload bounding* where thresholds are pre-configured for each work centre to explicitly limit the WIP on the shop floor (Bergamaschi et al., 1997). This threshold refers to the maximum and/or minimum workload limit of a work centre. These limits will in turn restricts the *backlog* at different levels (for example, release and planned backlog), where implication is being reflected at each hierarchical level. Thus, workload norm functions as a signalling tool between planning and control.

This signalling helps to avoid lead-time syndrome (LTS). LTS occurs when there is unrestricted release of jobs to work centres. This muddles the actual capacity of work centres and results in impractical planned lead time and late delivery. Seeing that jobs are always delivered late, jobs are released further ahead of time, with the hope that it will be delivered on time. On the contrary, instead of improving the situation, it turns into a vicious cycle. This further worsen shop floor congestion, increases lead time and reduces due date performance (Breithaupt et al., 2002; Wiendahl, 1995).

Instead of adopting rigid workload limit, there are other researchers who advocate explicit workload balancing by introducing additional rules on top of the basic workload norm at each work centre (Bergamaschi et al., 1997; Land and Gaalman, 1998). For example, to avoid jobs with relatively larger processing time being blocked from released, the probabilistic approach has introduced the automatic release of the first rejected job due to workload norm overload (Bechte, 1988). Hendry and Kingsman (1991) introduces rules to force release work orders categorised as *urgent*.

In addition, they also advocate the force release of work orders, which could provide lots of work for under-loaded work centres at the expense of causing minimal over-loading elsewhere. This method of relaxing maximum bound is also supported by Cigolini and Portioli-Staudacher (2002), where overall work balance improvement is desired by comparing the 'total impact' of over and under-loading work centres.

Another workload norm alternative is *Superfluous Load Avoidance Release* (SLAR) proposed by Land & Gaalman (1998). As highlighted by Stevenson (2006), this was built upon Starvation Avoidance (SA) release mechanism proposed by Glassey and Resende (1988), where jobs are released to avoid bottleneck work centres becoming idle. SLAR release mechanism focuses on the direct load of workstations.

If a workstation, *s*, finishes its direct load, a job in the pool with *s* being the first workstation on its routing and earliest planned start date will be released to *s*. Jobs classified as urgent is allowed to be released to its first workstation as long as there are no other urgent jobs at the required first workstation. If there are no urgent jobs and *s* has no other jobs, the job with shortest processing time on *s* is released. This simplifies the need to determine workload norm for work centres and is regarded as a starting point to control workload without using workload norm.

Referring to *Figure 3.7*, at this stage, only release backlog (RB) of each individual work centre is considered. This is represented by the following equation:

$$RB_{wd} = \sum_{i=1}^{I}[(Q_i \times PT_{iw}) + ST_{iw}] \qquad 3.4$$

where *i* is a released job with DD ≥ *d*; Q_i is the quantity of released job *i*; PT_{iw} is the unit processing time for released job *i* at work centre *w*; ST_{iw} is the setup time for released job *i* at work centre *w*. Release Backlog Length (RBL) is determined in similar way as for TBL and PBL.

3.2.4 Shop Floor Control Stage

This control stage is also referred to as the *priority dispatching* level, which concerns the day-to-day control on shop floor. As highlighted by Kingsman and Hendry (2002), for WLC approach to be effective, it is necessary to use both release mechanism and shop floor control together. Information obtained from shop floor control serves as a feedback loop to facilitate control at release stage. As a result, only simple dispatch priority is required on the shop floor such as simple first in first out (FIFO) dispatching rule (Hendry and Kingsman, 1989).

To facilitate the feedback process, focus is directed at the means to update job progress at each work centre. To ensure the functionality of DSS within WLC, Huang (2017) highlighted the importance of information flow both within the WLC system as well as between WLC and the external information systems to support DSS. A WLC information architecture is developed to highlight the critical data information required to facilitate practical implementation of WLC.

This architecture proposed by Huang (2017) categorises data information into three collection stages:

(i) Input Control: *Job Information*,
(ii) Output Control: *Capacity Information*, and
(iii) *Performance* measurement.

Of the three categories of information, the collection of *Capacity Information* is considered the most challenging. It is typically simplified as standard output rate of work centre (or machine). It is noted that in a practical MTO manufacturing environment which has a more complex capacity consideration, a more sophisticated measurement mechanism is required. This information is critical as it is used to determine the workload norm, or the size of protective buffer for each work centre (Fernandes et al., 2014).

Despite the relatively higher share of simulation-based journal articles in WLC, practical WLC implementation reported emphasises the importance of *human intervention* on shop floor (Hendry et al., 2013; Romero-Silva et al., 2015; Stevenson, 2006). Although in general, FIFO is used to make dispatch decision, in practice, due to the dynamic nature on shop floor, *tacit knowledge* of experience personnel is encouraged to be used in making the final dispatch decision.

3.2.5 Summary

WLC has become a generic umbrella term which includes research strands related to order review and release (ORR) method, input/output control (I/OC), load oriented manufacturing control (LOMC), and the integration of various ORR rules to control workload (ORR WLC) (Thurer et al., 2011). The fundamental principles underpinning WLC is summarised by Stevenson et al. (2011) as following:

(i) Total work input rate is controlled in accordance with the output rate;
(ii) Amount of WIP has to be explicitly controlled; and
(iii) Throughput times has to be stabilised to provide reliable product/service to customer.

Over the years, WLC has been developed and is considered a leading production planning and control (PPC) solution for make-to-order (MTO) companies (Land and Gaalman, 2009). The salient feature in LUMS WLC is the addition of customer enquiry stage into its DSS developed. It has four hierarchical planning stages with three control points: *Customer Enquiry*, *Job Entry*, *Job Release*, and *Shop Floor Control* (Stevenson, 2006a). The main purpose is to enable quoted delivery due date, reliable due date, and job release date to be determined based on loading and available capacity. Associated decisions such as negotiation or re-negotiation of delivery dates, prioritisation of job, or activation of buffer capacity can be made accordingly. Detailed equations and necessary detailed data information to be collected to facilitate calculation can be found in Stevenson (2006a), Hendry et al. (2013) and Huang (2017). Having reviewed WLC, the PPC for MTO advocated by academia, the next section, Section 2.3, will review S-DBR, the PPC for MTO advocated by TOC practitioners.

3.3 Simplified Drum-Buffer-Rope (S-DBR)

S-DBR is a further development of TOC application for MTO manufacturing environment by Schragenheim (2000). This section will begin with an overview on TOC. This is followed by a critical review on its development of applications in MTO: Drum-Buffer-Rope (DBR) and S-DBR. Strategy & Tactic (S&T) tree concept will also be briefly introduced as it is a method used in TOC to capture and proliferate TOC knowledge. Implementation guide on S-DBR is recorded in the form of S&T tree for TOC practitioners. This guide will be reviewed to inform the research described in this document.

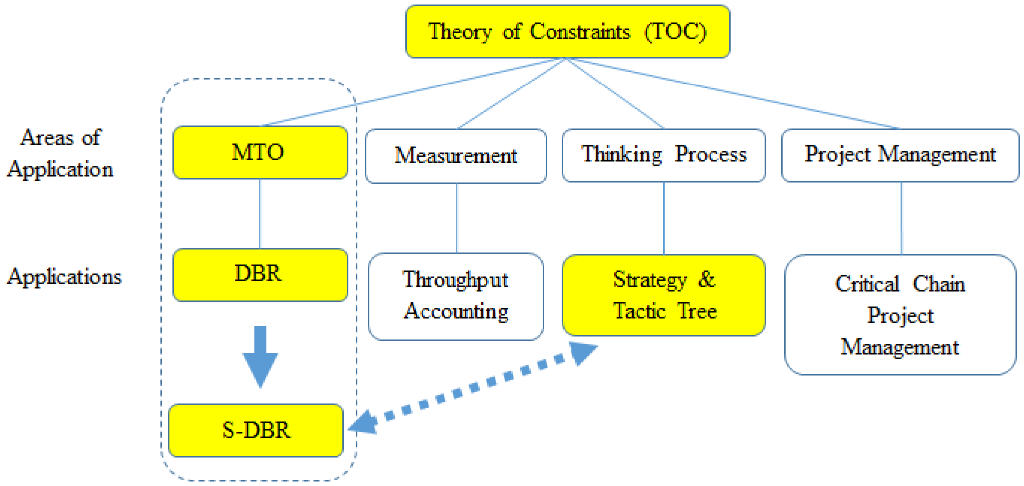


Figure 3.10: TOC and the relevant applications to be discussed (highlighted)

3.3.1 Introduction to Theory of Constraints (TOC)

Since the inception of Theory of Constraints (TOC) in the late 1970s, it has evolved from a commercial production software into a management philosophy. Authors such as Watson et al. (2007) and Simsit et al. (2014) have well illustrated the evolution of TOC in five eras:

- (1979 – 1984) The era of *Optimised Production Technology (OPT)* – 'Secret' Algorithm
- (1984 – 1990) The era of *The Goal* – Drum-Buffer-Rope Scheduling
- (1990 – 1994) The era of *The Haystack Syndrome* – TOC Measures
- (1994 – 1997) The era of *It's Not Luck* – Thinking Process
- (1997 – 2004) The era of *Critical Chain* – Project Management
- (2004 – Present) The era of *Viable Vision* – The Proliferation

The TOC journey begun with a practical real-world problem, a request from Goldratt's neighbour to develop a schedule to increase output of a production plant (Brylinski, 1983). The initial success in OPT deployment spread within the practitioner world with its concept explained in APICS (Goldratt, 1980; 1981). OPT, in its *algorithm layer*, generates master production schedules (MPS) for bottleneck resources through forward scheduling. Schedule for non-bottleneck resources is generated by means of backward scheduling based on the prior generated MPS. Within scheduling, elements such as capacity, availability and routing are taken into consideration.

This scheduling algorithm resembles Kanban where 'station stock limitation' (SSL) is created in between operations. Production is only allowed if the inventory level falls below SSL. Unlike Kanban, each operation is assigned a variable minimum batch quantity (MBQ) to be produced. This is described as an 'automated Kanban' by Goldratt (1980; 1988). Sophisticated technique has been used to produce optimum schedules. According to Goldratt (1988), the complexity has "*made the analyst's task of understanding the schedules much more complex*". Details of OPT algorithm is illustrated by Fry et al. (1992) and Bond (1993).

Although OPT software is meant to produce an accurate schedule, through practical implementations, Goldratt (1988) acknowledges the reliance of the algorithm on accurate data feedback from the shop floor. The feedback is highly dependent on shop floor personnel's understanding of the schedule and the concept behind it. The introduction of OPT created controversies as it abolishes local optima, allowing certain resources to be kept busy while allowing some to stay idle. This creates contradiction between balance-flow and balance-capacity. The systemic view advocated in OPT also challenges the existing performance measurement system, where performance is based on individual resource utilisation rather than systemic throughput.

Realising the importance of understanding the concept behind OPT, nine OPT rules were introduced to make known the 'philosophical layer' of OPT. (Goldratt and Fox, 1986). As described by Goldratt (1988), "*the software [OPT]'s superiority stemmed not from its algorithm, but mainly from these underlying concepts*". These nine rules of OPT are as follow:

1. *Balance flow, not capacity.*
2. *Level of utilisation of a non-bottleneck is determined not by its own potential but by some other constraint in the system.*
3. *Utilisation and activation of a resource are not synonymous.*
4. *An hour lost at a bottleneck is an hour lost for the total system.*
5. *An hour saved at a non-bottleneck is just a mirage.*
6. *Bottlenecks govern both throughput and inventory in the system.*
7. *A transfer batch may not, and many times should not, be equal to the process batch.*
8. *The process batch should be variable, not fixed.*
9. *Schedules should be established by looking at all of the constraints simultaneously. Lead times are a result of a schedule and cannot be predetermined.*

Through various practical implementations of OPT, the concept of using *time* as a protective buffer mechanism, and the use of buffer management are conceived. Realising the importance of understanding the *philosophical layer* of TOC by the managers and workers, the book called *The Goal* (Goldratt and Cox, 1984) was written, using a novel to describe the foundation for TOC practice. It simplifies further the nine OPT rules into the Five Focusing Steps (5FS) to guide implementation of TOC. Together with two pre-requisites, 5FS has evolved into the current Process of On-Going Improvement (POOGI). According to the TOCICO dictionary (Cox et al., 2012), the definition of each step is as below:

- Pre-requisite 1: Define the system under investigation.
- Pre-requisite 2: Define measurements that align the system to that purpose.
- Step 1: IDENTIFY the system’s constraint(s).
- Step 2: Decide how to EXPLOIT the system’s constraint(s).
- Step 3: SUBORDINATE everything else to the above decision.
- Step 4: ELEVATE the system’s constraint(s).
- Step 5: WARNING!!!! If in the previous steps a constraint has been broken, go back to step 1, but do not allow INERTIA to cause a system’s constraint.

A production scheduling concept was introduced in *The Goal*: Drum-Buffer-Rope (DBR). The definition of DBR according to TOCICO (Theory of Constraints International Certification Organisation) dictionary (Cox et al., 2012):
'*The TOC method for scheduling and managing operations. Usage: DBR uses the following:*

1. *The drum, generally the constraint or CCR'* (Capacity Constraint Resource), *'which processes work in a specific sequence based on the customer requested due date and the finite capacity of the resource;*
2. *Time buffers which protect the shipping schedule from variability; and*
3. *A rope mechanism to choke the release of raw materials to match consumption at the constraint.*'

Details on DBR will be further discussed in section 3.3.3, 3.3.4 and 3.3.5 of this document.

Realising the existence of the human attitude of: '*Tell me how you measure me, and I will tell you how I behave*' (Goldratt, 1990:26), TOC evolves further to challenge the *sacred cow*: *cost accounting,* in the financial world by introducing the concept of Throughput Accounting (TA) (Goldratt, 1990). It is argued that *cost accounting* is based on *historical data,* which is not able to adequately support informed decision making for the future. This is supported by Smith (2000:44) who views the traditional accounting practice as a mere *reporting tool* for past activities. It is inadequate in allowing management to strategize actions, which maximises throughput and cash flow for now and in the future. This deficiency was also realised by Johnson and Kaplan (1997) which then developed Activity Based Costing.

Throughput accounting (TA) is a process focused framework which allows organisation to focus on actions which improves overall financial performance (Watson et al., 2007). Other than challenging the underpinning assumptions of corporate financial structure, Goldratt and Cox (1984) also view performance measurement of each individual resources from similar perspective, focusing on Throughput (T), Investment (I) and Operating Expenses (OE). Instead of focusing on *cost reduction* which has a *limit*, the new perspective focuses on increasing company *throughput*, by introducing the concept of *Contribution per Constraint minute*

(CPCM) (Gardiner and Blackstone, 1991). By using CPCM, management can make informed decisions to achieve highest throughput based on constraint resources.

Acknowledging that every organisation is complex and unique, Goldratt (1994) subsequently introduced a systematic and logic way of identifying and arriving at a possible solution to the root cause: The *Thinking Process* (TP). The TP tools consists of Current Reality Tree (CRT), Future Reality Tree (FRT), Transition Tree (TT), Evaporating Cloud (EC), and Prerequisite Tree (PRT). These tools utilise sufficient cause, effect-cause-effect and necessary condition logic to identify hidden assumptions which hinders effective solution implementation. Its application has been well described by researchers such as Kim et al. (2008) and Mabin et al. (2001). The usage of TP has also been further developed to help management arrive at strategic decisions where Strategy and Tactic (S&T) Tree has been developed according to TOC contextual applications (Goldratt et al., 2002). Generic S&T for each TOC application is used as an implementation guide for practitioners. Details on S&T Tree will be further illustrated in section 2.3.6 of this document.

The challenges faced in project management (PM) has prompted Goldratt (1997) to apply TOC logic into the PM environment and introduced Critical Chain Project Management (CCPM). Although bearing similarity to critical path project management (CPM), it has three major differences in activity times, buffer usage, and resource utilisation (Watson et al., 2007). In CPM, with the argument to protect each individual task to finish as committed, additional buffers are built into each individual task. Due to *Parkinson's Law*, tasks will naturally spread to utilise all allocated time, including buffer time (Parkinson, 1955). If any of these individual tasks is late, it will cause the delivery time of the overall project to be late. Instead, CCPM suggests one aggregated buffer to be deployed towards the end of the project. This allows protection against entire project delivery. Traditional critical path PM ignores resource conflict, which will result in similar resource being assigned to multiple individual tasks simultaneously, resulting non-realistic project end date. CCPM overcomes this by considering both longest aggregate project completion time as well as resource contention.

In the present era, in the practitioner world, TOC body of knowledge is developed and proliferated mainly via TOCICO (Theory of Constraints International Certification

Organisation), its members and affiliated institutions and organisations. Academically, Watson et al. (2007) has provided an account on the history and development of TOC. TOC literature and its successful application has been well reviewed by researchers such as Rahman (1998), Balderstone and Mabin (1998), Mabin and Balderstone (2003), Gupta (2003) and Kim et al. (2008). In the field of OM, TOC is advocated as a general and unifying theory (Gupta and Boyd, 2008). It has also been recognised as one of the few significant theories in OM (Boer et al., 2015). A further contribution of TOC in OM is explored by placing it in position with operations research/management science methodologies (Davies et al., 2005). To assist in understanding various aspects of TOC, a collective contribution from practitioners and researchers are captured in the 'Theory of Constraints Handbook' (Cox and Schleier, 2010).

Despite these efforts, one of its more recent development: S-DBR has received relatively low attention by researchers (Benavides and Van Landeghem, 2015). This is evident with a search on EBSCO (Business Source Complete) database with the term 'S-DBR' (returned two results) or 'SDBR' (returned six results with one relevant) or 'Simplified Drum Buffer Rope' (returned four results with three relevant). The list of journal articles on S-DBR is shown in *Table 3.2*.

Of the six journal papers, five are related to manufacturing environment. As this review focuses on manufacturing, only papers relevant to manufacturing are reviewed and discussed. Although three out of the five papers are empirical research, only two of them involves the researcher in the implementation process. Of these two papers, although one highlights the successful implementation and the need to develop an organisation centric PPC, the case company did not offer opportunity to explore the need to adapt the generic S-DBR according to contextual environment.

As highlighted by researchers, additional research on the validity and effectiveness of the generic S&T for S-DBR is necessary (Hwang et al., 2011). Thus, it is the purpose of this research to contribute towards the TOC body of knowledge, particularly in the S-DBR area. Having introduced TOC and its development, the next section, section 3.3.2, will critically review S-DBR and its relevance as a PPC in MTO environment.

Table 3.2: List of S-DBR Journal Publication

Title	Journal	Author	Year	Research Method	TOC Body of Knowledge	Manufacturing Environment	Significance of Touch Time	Implementation/ Contextual adaptation	Results/ Conclusion/ Contribution
Research on enhancement of TOC Simplified Drum-Buffer-Rope system using novel generic procedures	Expert Systems with Applications	Lee, J.; Chang, J.; Tsai, C.; Li, R.	2010	Non-empirical - Conceptual	SDBR Plan Load/Buffer Management	- MTO	Impact of CCR location on buffer effectiveness has positive correlation with significance of touch time	- Challenges the generic assumption in determining order release date where CCR is assumed to be located in the middle of a process routing where order release date is taken as first available time slot + ½ of production buffer. - Proposed enhanced order release date according to position of CCR: front or end, by multiplying with a factor.	It is anticipated that if CCR is located at the front, order will not be released too early; If CCR is towards the end, order will be released earlier in to offer sufficient time buffer
Using Simplified Drum-Buffer-Rope to Rapidly Improve Operational Performance: A Case Study in China	Production and Inventory Management Journal	Hwang, Y. J.; Huang C.; Li, R. K.	2011	Empirical - Case Study	SDBR S&T Tree	- MTO - Average Lead Time: 60 days - Touch Time: ≤ 2 days	- (2/60) x 100% ≈ 3.33 % - Insignificant	- Setting production buffers - Generating and obeying release schedule - Freezing excessive WIP - Creation of buffer zones - Buffer meetings - Identify CCRs - Target loading of CCR	- Housekeeping work on shop floor to straighten records - Utilise manual colour coding on work orders and displayed on blackboard - WIP ↓by 22% - Capacity ↑ by 28 % - Demonstrated successful use of S-DBR S&T to deploy S-DBR

Addressing Food Production Planning and Control Issues through Information Visualisation: An Agile Development	Communications of the IIMA	Allison, I.; Stratton, R.; Robey, D.	2012	Empirical – Action Research	SDBR S&T Tree	- MTO	-Insignificant		- Improved information visibility - Revenue ↑ by 250 % with reduction in operating cost and inventories
An enhanced model for SDBR in a random re-entrant flow shop environment	International Journal of Production Research	Chang, Y.; Huang, W.	2014	Non-empirical - Simulation	SDBR S&T Tree	- MTO with re-entrant flow			- Include all CCR used in every re-entrant process into consideration - Re-order work order priority at CCR according to the overall buffer status with weightage indexed according to number of re-entrant.
Implementation of S-DBR in four manufacturing SMEs: a research case study	Production Planning & Control	Benavides, M. B.; Van Landeghem, H.	2015	Empirical - Case Study: Cross Case analysis between four SME Companies	SDBR S&T	Case A: 98% MTO, 2% MTS Case B: 90% MTO, 10% MTS Case C: 95% MTO, 5% MTS Case D: 100% MTO	- Insignificant	- Case A and C: CCR location at the beginning of routing. Introduced single flexible shipping buffer.	Four types of Measurement Used: i) Time related ii) Dependability iii) Shop-related iv) Financially related Importance of contextual adaptation
Improving labour relations performance using a Simplified Drum Buffer Rope (S-DBR) technique	Production Planning & Control	Chakravorty, S. S.; Hales, D. N.	2016	Empirical - Case Study	SDBR S&T	Service Industry			Reduced mean lead time from 30 days to 10 days.

3.3.2 PPC from the Perspective of TOC

The perspective of TOC on PPC solution is well described by Schragenheim (2010:213-217). The first perspective is the concept of *flow*. Like the production systems introduced by Ford and Ohno, TOC views flow improvement as the primary objective of operations (Goldratt, 2009). To improve flow, these production systems have implemented practical mechanism to prevent over-production. Ford uses *space,* Ohno uses *inventory* and TOC uses *time*. To enable flow, these mechanisms adopts a systemic view and abolish local efficiencies. In addition, focusing process (for improvement) is used in these production systems to achieve balanced flow. Ford utilises 'direct observation' whereas Ohno practices the gradual reduction of inventory in between work centres.

In TOC, both constraint management (with its 5FS) and buffer management are used to target improvement. The second perspective concerns the *planning* and *execution* in PPC. In OPT, *bottleneck* resources are scheduled in detail followed by the *non-bottleneck* resources. As the planning stage is performed in detail, its execution stage is only to strictly follow the given schedule. In DBR, during planning stage, detailed schedule is only performed for the *bottleneck* resource. The other point where detailed schedule exists is the material release point, with the purpose to prevent over-production. This is achieved via the 5FS and DBR mechanism, which is also known as the *Constraint Management* (Boyd and Gupta, 2004).

As highlighted by Schragenheim (2010:213), PPC under TOC acknowledges the challenges of planning and execution in a practical world where uncertainties exist. Rather than using PPC to realise optimisation in an assumed deterministic world, TOC has evolved into providing simple solutions with rules to guide decision-making when uncertainties arise. The move of TOC PPC application towards *minimum planning* means additional responsibility falls in the execution stage. This is achieved by the introduction of decision-making rules using *Buffer Management*. As the TOC PPC solution further evolves into S-DBR, it is necessary to understand the implications to both the *planning* and *execution* stages in PPC.

S-DBR is a PPC application for make-to-order (MTO) manufacturing environment proposed by Schragenheim (2000). As a further development based on its predecessor, DBR, its conceptual details are well described in Schragenheim and Dettmer (2000), Schragenheim et al. (2009) and Schragenheim (2010). The subsequent sections will review S-DBR and DBR from three perspective: section 3.3.3: Constraint Management (CM), section 3.3.4: Buffer Management, and Section 3.3.5: Load Management.

3.3.3 Constraint Management (CM)

According to TOCICO dictionary, *Constraint* refers to the *factor*, which ultimately limits the performance of a system or organisation (Cox et al., 2012). Both DBR and S-DBR systems adopt a systemic view, where throughput of a production system is determined by the constraint within a system. Thus, managing the constraint of a system will directly impact the system flow performance (Goldratt, 1984; Schmenner and Swink, 1998).

In a production system, resource with the least throughput performance is known as the Capacity Constraint Resource (CCR). The throughput of the entire production system is limited by the throughput of the CCR. In TOC, this CCR is known as the *Drum* in the system. Since the *Drum* dictates the pace of the entire system, it is not necessary to introduce jobs that are more than what the *Drum* can process. Overloading the system will only introduce excess work-in-process (WIP) into the system. A master schedule is determined based on the finite capacity of the *Drum* (Betterton and Cox, 2009).

Control over the release of jobs into the system is achieved by tying a *Rope* between the *Drum* and the first workstation of the production system, which releases raw materials into the system. *Rope* acts as a mechanism to explicitly control the WIP within a system according to the *system capacity* by choking the early release of raw materials into the system (Cox et al., 2012).

With the acknowledgment of the criticality of CCR to system performance, it is necessary to ensure CCR is protected against uncertainties, be *exploited* to perform according to its capacity. *Buffer* is introduced to protect CCR against any *starvation*. According to the TOC dictionary, *starvation* refers to a situation where a constraint is left idle due to lack of material to process. Thus, the status of *Buffer* is used as a signal to determine the release of raw materials into the system.

In DBR, the general assumption for *Constraint* is a CCR within the production system, though market can also be regarded as one of the constraint factors. By placing additional business strategy perspective into CM, Schragenheim and Dettmer (2000:157) argues that it is external *market demand* rather than internal *resource capacity* which often acts as the ultimate limiting factor to system performance. Internal constraint comes and go, whereas *market demand* will always remain a constraint.

In DBR, as all other elements in the system must be subordinated to the internal CCR, this causes customer orders with potentially higher long-term benefits to be rejected. The detailed schedule created at CCR via finite capacity scheduling causes the system to be less flexible in responding to market demand such as urgent orders. In an MTO environment where the ability to provide safe and reliable due date is critical, *market demand* naturally acts as the *Drum* which dictates the pace of the system.

Instead of *Internal Constraint*, S-DBR sees beyond resources used within production process and assume *market demand* as the ultimate performance limiting factor. By placing the *Constraint* to the end of the production system, it changes the way *Buffer* is being deployed and used in the system. A detailed discussion on *Buffer* will be given in section 3.3.4: Buffer Management (BM).

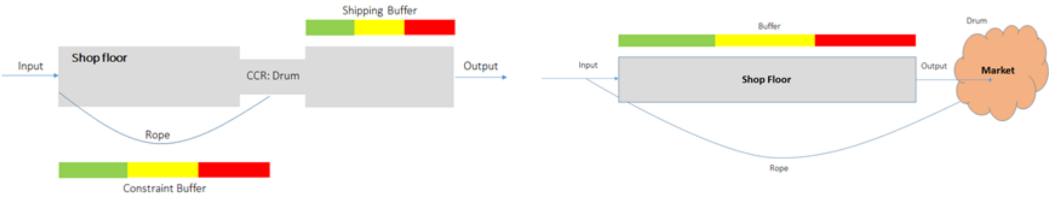
3.3.4 Buffer Management (BM)

According to the TOCICO definition, *buffer* is protection against uncertainty. It may take the form of time, inventory, capacity, space or money (Cox III et al., 2012). In both DBR and S-DBR, buffer is strategically deployed at critical areas to protect them against disruption (Goldratt and Cox, 1984; Schragenheim and Ronen, 1990; 1991). Disruption can be from all sources as illustrated by Hopp and Spearman (2004) in law of variability pooling. As discussed in section 3.3.3, the pace of the system is dictated by system constraint. Thus, it is obvious to have a buffer deployed at the upstream of system constraint to protect it against disruption.

In addition to *Constraint Buffer*, there are two other types of buffers in DBR: *Shipping Buffers* and *Assembly Buffers*. While *Constraint Buffer* is deployed to protect throughput of CCR, buffers are also deployed at other control points such assembly and shipping points. *Shipping Buffer* is deployed at the end of the production process.

The purpose is to protect the entire production process flow against any disruption at any point to derail from delivery time commitment (Srikanth, 2010:186). *Shipping Buffer* is added onto *Constraint Buffer* to determine the safe delivery date. In addition, *Shipping Buffer* is also used to dictate the release date of jobs or parts which does not go through CCR (Cox III et al., 2012). *Assembly Buffer* is applicable if there are assembly points within a production system. It is to ensure availability of all necessary assembly parts to avoid causing disruption to the system flow (Simatupang, 2000).

Unlike DBR, S-DBR always assumes *market demand* as the system's *Constraint*, placing it right at the end of the production system. This eliminates the complexity of needing multiple buffers and aggregates all buffers before the '*market demand*', as illustrated in *Figure 2.9*. It resembles a DBR system without CCR, and thus reduced to deploying only *Shipping Buffer*. In S-DBR, this aggregated buffer is known as *Production Buffer* (PB) rather than *Shipping Buffer*. Further details on *Production Buffer* will be discussed towards the end of this section.



(a) DBR (b) S-DBR

Figure 3.11: Concept of TOC MTO Application

In MTO application, time is used as buffer in both DBR and S-DBR. According to Schragenheim (2010:213), this concept is to '*release the materials for the bottleneck exactly a time-buffer length before the bottleneck is supposed to begin work on the job, giving all the required resources enough time to let the parts reach the bottleneck before the scheduled time*'. This will provide a significant reliability in satisfying market demand (Srikanth, 2010: 186). For buffer to effectively protect a system against variabilities and uncertainties, buffer needs to be effectively managed so that it is able to provide timely and meaningful *Signal*. According to TOCICO dictionary (Cox III et al., 2012), BM is a time-based control mechanism with the following four main functions:

1. To *prioritise* tasks/orders based on buffer penetration/consumption.
2. To *expedite* tasks/orders that are at risk of missing promised due date.
3. To *feedback* any necessary buffer design parameters or *escalate* if requires decision making by higher management (Stratton and Knight, 2010).
4. To *target* areas and engage in ongoing improvement activities (Stratton and Knight, 2009).

The above main functions show the significant role of BM in both DBR and SDBR. It is used as a diagnostic tool to *signal* the *health statuses* of the production system (Schragenheim and Ronen, 1991; Blackstone, 2010:161). The implementation of BM for DBR is well described by Schragenheim and Ronen (1990, 1991) and Simatupang (2000). Firstly, time buffer is divided into three *buffer regions*, represented by *Red*, *Yellow* and *Green* colours.

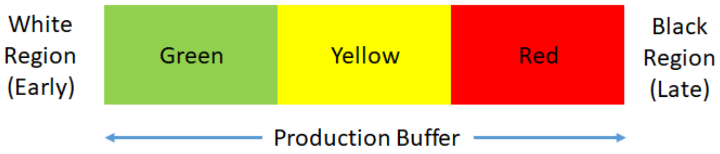


Figure 3.12: Buffer Regions in Buffer Management

According to TOCICO dictionary (Cox III et al., 2012), *buffer regions* provides indication for necessary proactive actions to avoid delays or starvation of a *Constraint*. Generally, each *buffer region* is set as one third of the total buffer size. In a conventional setting, the *buffer size*, as recommended in TOCICO dictionary is to be half of the original lead time. However, it is noted that both *buffer region* and *buffer size* have to be adapted according to contextual characteristics of process flow and product.

Other colours are used to indicate two regions outside of the *buffer regions*: orders released ahead of schedule (early release), and late orders (which usually coloured as *black*), as illustrated in *Figure 3.12*. If a job is in the Green region, it signals that the job can be released into the system; Yellow region signals a job should be released into the system, and Red region sends an alert where job has to be prioritised. If required, the situation will be escalated to higher management for higher level intervention. Inquiries are conducted on jobs in Red and Black region with reasons captured for continuous improvement.

With regards to the suitability of DBR to be used in MTO manufacturing environment, Hendry and Kingsman (1989) opined that DBR is more suitable for MTS (Make-To-Stock) environment as it falls short of addressing the customer enquiry stage, a vital component in MTO. This was again highlighted by Stevenson et al. (2005) in stating that '*TOC does not directly cater for the importance of planning and control at the customer enquiry and job entry stages in MTO production*'.

Although DBR concept requires both CM and BM to work together, it is often misunderstood as a mere 'bottleneck' or CM solution (Boer et al., 2015:1235; Schmenner and Swink, 1998:101; Spearman, 1997). The importance of *Buffer Management* at both the conceptual and implementation levels are neglected by researchers. As stressed by Schragenheim (2010: 211; 229), both CM and BM are not stand-alone methods. Rather, both are essential in DBR to realise control at three critical points: 1) *Due dates for all orders*; 2) *Detailed schedule of CCR*; and 3) *Schedule for the material release*. Detailed schedule at CCR allows production system to be paced according to system capacity. Based on system capacity, due dates for orders can be determined in customer enquiry stage. Through buffer management, signal is given to the job entry stage to choke or release material.

3.3.5 Load Management (LM)

As discussed in section 3.3.3, S-DBR adopts *market demand* as the *drum* which dictates the pace of the system. This moves away from keeping a detailed schedule for CCR. Instead, S-DBR introduces a new element: *Planned Load* (PL). According to the TOCICO dictionary, PL means '*the total load on a resource of all the firm orders that have to be delivered within a certain horizon of time. The time horizon used to determine the planned load is generally longer than the production buffer by at least a factor of two. The planned load is used* extensively *to ensure smooth flow and to make due date commitments that can be reliably achieved*'.

PL is used to monitor all current active and in-queue jobs on potential CCR within the system (Schragenheim, 2010:180). Based on the loading information available through PL, both the delivery due date and schedule order release date can be determined. With the assumption that the position of CCR is in the middle of the production process, delivery due date is proposed to be the sum of half of the production buffer plus the next available time slot at the CCR.

Using the example shown in *Figure 3.13*, if the lead time for a product is 10 days, the order due date is determined by adding half of necessary lead time (5 days) to the first available time slot on PL (day 9). Thus, the order due date will be end of day 14 or beginning of day 15. The raw material release date is determined by subtracting 5 days from the earliest available time slot at PL, which is day 4.

The use of PL to determine order due date *smoothen* the workload at CCR, which directly smoothens the *flow* within the system. In addition, it reduces the risk of CCR becoming the contributing factor to any late deliveries. This is with the assumption that under normal circumstances, all the required processes of the work order at upstream work centres can be completed and arrive in time at the CCR to be processed. The downstream work centres, with a larger capacity than CCR, will then continue to complete the remaining processes with road runner attitude. This assumption is only valid for cases where CCR is in the middle of the process route.

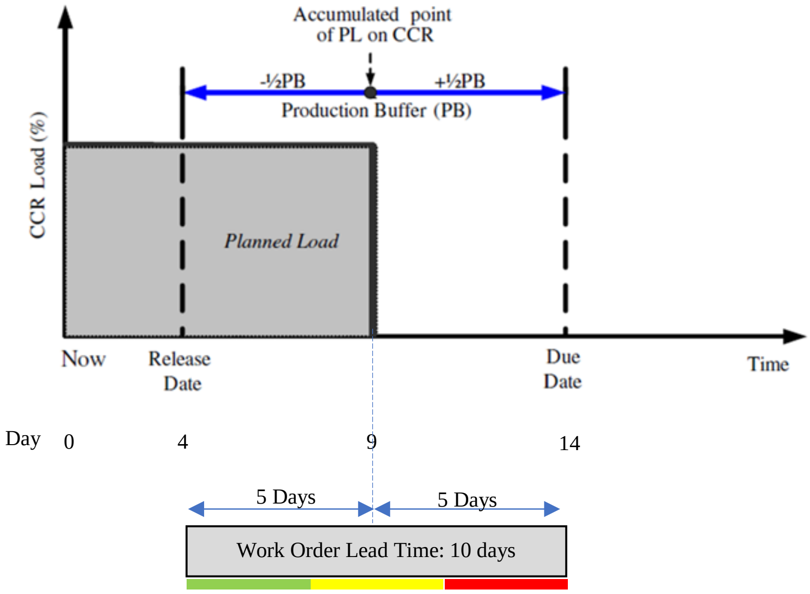


Figure 3.13: Planned Load in S-DBR

According to Lee et al. (2010), for situations where the location of CCR is at the front end of routing, orders might be released into the system too early. In the case where CCR is located at the back end of the process routing, it might cause orders to be released too late, causing inadequate buffer protection. To improve this situation, they have suggested an improvement to the generic S-DBR. For cases where CCR is located at the front end of the routing:

$Order\ Due\ Date = (1 - \alpha)PB + first\ available\ time\ slot\ on\ CCR$
$Order\ Release\ Date = first\ available\ time\ slot\ on\ CCR - \alpha PB$, where $\alpha < 0.5$

If CCR is located at the back end of the routing:

$Order\ Due\ Date = (1 - \beta)PB + first\ available\ time\ slot\ on\ CCR$
$Order\ Release\ Date = first\ available\ time\ slot\ on\ CCR - \beta PB$, where $\beta > 0.5$

However, the authors did not explicitly discuss how the final value of α and β are determined. It might possibly be determined based on the relative position of CCR within the PB.

Another contextual dependent improvement to S-DBR was suggested by Chang and Huang (2014) on re-entrant flow shop environment. This refers to cases where work order revisits one or multiple resources more than once. The authors introduce the concept of *Total Planned Load* and *Weighted Layer Buffer Status*, where the total CCR usage for every re-entrant process is obtained. Weightage is placed onto orders depending on re-entrant numbers. From the simulation conducted using real company data, it is shown that it provides better performance than the generic S-DBR.

Based on the above discussions on S-DBR, and the discussion by Benavides and Van Landeghem (2015), the similarities and differences between DBR and S-DBR is summarised in *Table 3.3*.

Table 3.3: Comparison between DBR and S-DBR
Adapted from Benavides and Van Landeghem (2015)

	DBR	S-DBR
Constraint Management	• System throughput is dictated by internal active CCR • Constraint buffer, Shipping buffer and Assembly buffer are deployed to protect CCR • Optimised throughput through detailed scheduling	• System throughput is dictated by Market • Production buffer is used to protect promised delivery due date
Buffer Management	• Work orders are prioritised according to the percentage of lead time consumption • More than one buffer to be monitored, could result in multiple priority list	• Work orders are prioritised based on buffer penetration on production buffer with consideration of total touch time (actual time spent on product) • Only single buffer to be monitored, single priority list
Load Management	• Detailed finite capacity scheduling of the CCR which is to be followed strictly by shop floor.	• Monitor Planned Load of potential CCR. • Planned Load is used to: • Determine Material Release Date, • Determine Delivery Due Date, • Monitor Potential CCR • No detailed schedule required. It does not dictate any order sequencing • Lead time is anticipated to be shortened due to buffer aggregation • Load at potential CCR is ‘smoothen’ by quoting delivery date according to current loading of potential CCR
Focus	• Maximum exploitation of CCR with all elements subordinated to it.	• Satisfying market demand
Coordination with Sales/Marketing Department	• Assume delivery date is fixed, shop floor. DBR does not explicitly allow due date to be checked without placing an order into the system.	• Explicitly includes ‘Safe Date’ determination for new orders through planned load.

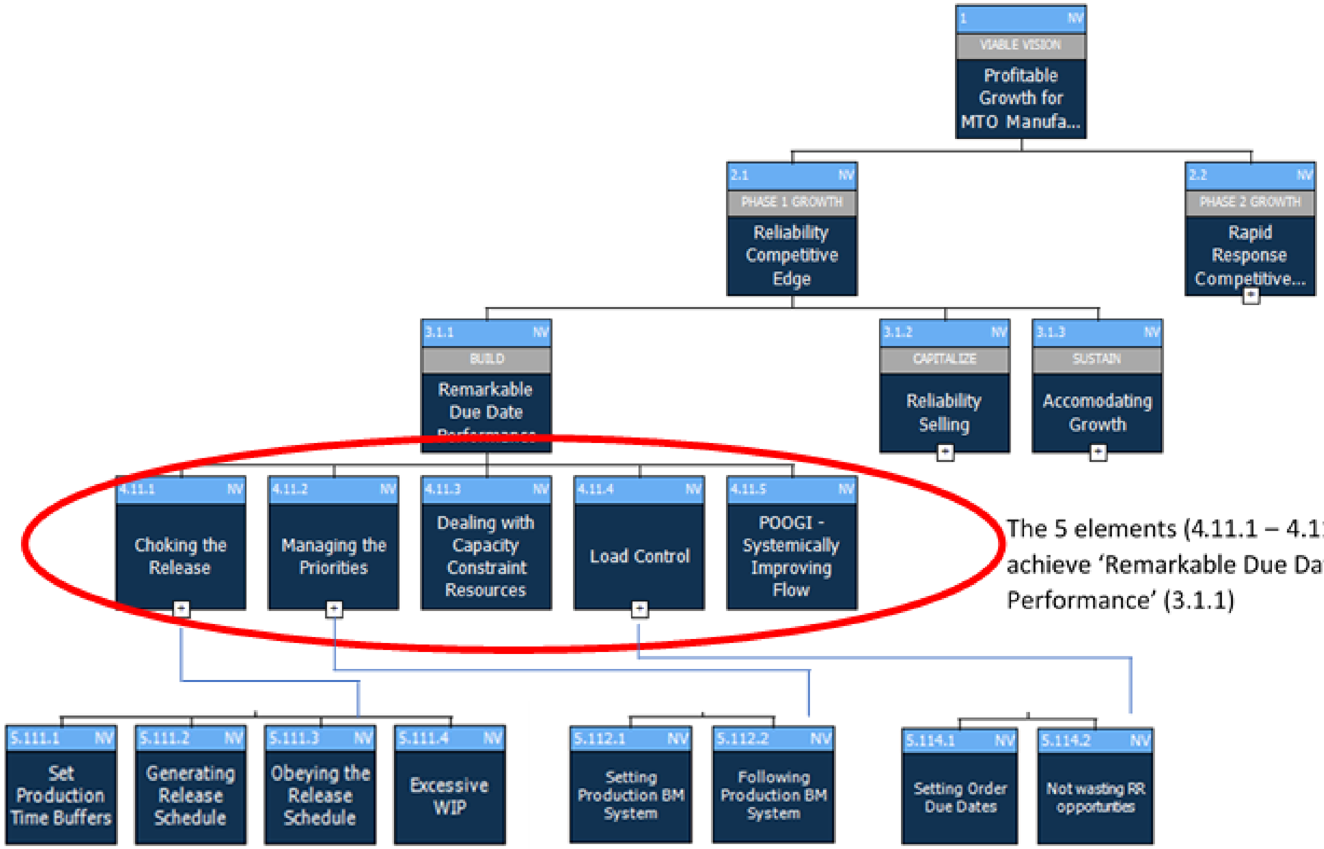
3.3.6 Implementation of S-DBR

Strategy & Tactic (S&T) tree is used by TOC practitioners as a change management tool (Dettmer, 2007; Kim et al., 2008; Mabin and Balderstone, 2003; Scheinkopf, 2010). It was firstly introduced by Goldratt (1994) and is used to capture and proliferate the generic TOC body of knowledge developed. It is structured to provide a step-by-step guide for practitioners to implement TOC. Other than being used as a *guide*, it is also used as a *tool* to capture new contextual knowledge captured throughout the implementation process. Based on the *new knowledge* captured, a new S&T is produced. This *contextualised* S&T is used as a basis to inform and support a company's continuous improvement effort. The structure of an S&T tree is shown in *Figure 3.14*. For each S&T element, it is an *inquiry process* into making a change (Barnard, 2010:444):

- *Why the change is needed (necessary assumptions)?*
- *What the specific measurable objective is for the change (strategy)?*
- *Why the objective is possible and why the tactic is the 'best' way (parallel assumptions)? How to best achieve the objective of the change (tactic)?*
- *What advice or warning should be given to subordinates which might jeopardise the sufficiency of the steps in implementing the tactic (sufficiency assumption)?*

Figure 3.14: S&T Tree Structure

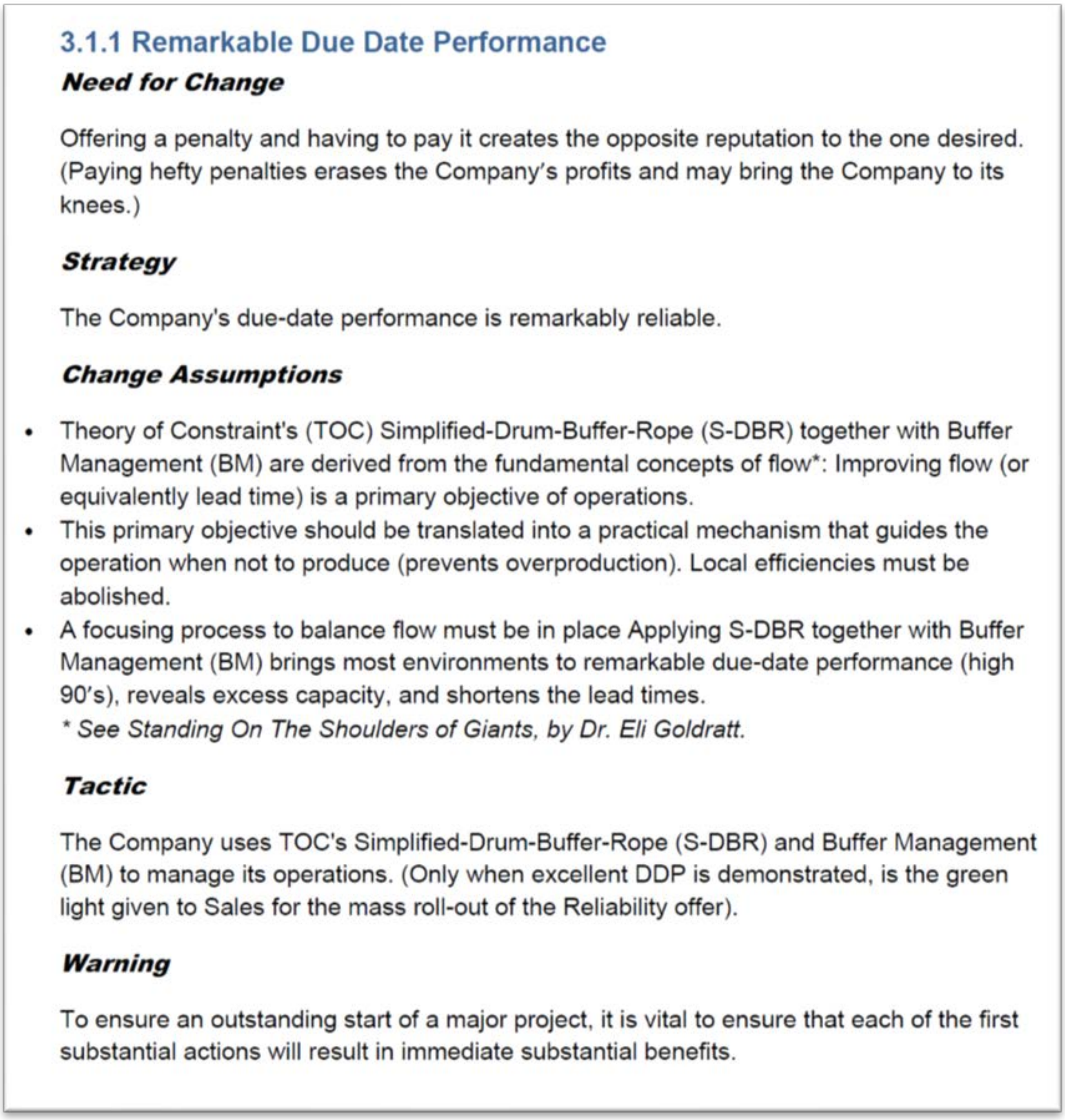
This inquiry process embraces the mapping of cause and effect (necessity and sufficiency) logic using abductive reasoning together with means of exposing and challenge assumptions in the resolution of conflicts (necessity logic). This approach makes the embedded assumptions in such interventions explicit (necessity, parallel and sufficiency) and at the same time capturing the knowledge generated throughout the change process. The generic S&T tree for S-DBR is shown in *Figure 3.15*. The details within an element is as shown in *Figure 3.16* using Element 3.1.1: *Remarkable Due Date Performance* as an example.



The 5 elements (4.11.1 – 4.11.5) needed to achieve 'Remarkable Due Date Performance' (3.1.1)

Figure 3.15: Levels 1 to 5 of Generic S&T tree for S-DBR

Source: Harmony, 2017



3.1.1 Remarkable Due Date Performance

Need for Change

Offering a penalty and having to pay it creates the opposite reputation to the one desired. (Paying hefty penalties erases the Company's profits and may bring the Company to its knees.)

Strategy

The Company's due-date performance is remarkably reliable.

Change Assumptions

- Theory of Constraint's (TOC) Simplified-Drum-Buffer-Rope (S-DBR) together with Buffer Management (BM) are derived from the fundamental concepts of flow*: Improving flow (or equivalently lead time) is a primary objective of operations.
- This primary objective should be translated into a practical mechanism that guides the operation when not to produce (prevents overproduction). Local efficiencies must be abolished.
- A focusing process to balance flow must be in place Applying S-DBR together with Buffer Management (BM) brings most environments to remarkable due-date performance (high 90's), reveals excess capacity, and shortens the lead times.

** See Standing On The Shoulders of Giants, by Dr. Eli Goldratt.*

Tactic

The Company uses TOC's Simplified-Drum-Buffer-Rope (S-DBR) and Buffer Management (BM) to manage its operations. (Only when excellent DDP is demonstrated, is the green light given to Sales for the mass roll-out of the Reliability offer).

Warning

To ensure an outstanding start of a major project, it is vital to ensure that each of the first substantial actions will result in immediate substantial benefits.

Figure 3.16: Element 3.1.1 in generic S-DBR S&T tree
Source: Harmony, 2017

The S&T for S-DBR will be used as the S-DBR implementation guide in this research project. Having discussed the generic implementation guide for S-DBR, the next section will continue to discuss the underlying assumptions used in S-DBR.

3.3.7 Assumptions in S-DBR

As in any system, there are assumptions and boundaries which limits the applicability of a system. According to Schragenheim (2010:234), for S-DBR to be ‘suitable’ to be implemented, there are two necessary conditions:

(i) *Arbitrary sequence of processing the orders does not significantly impact the capacity of the resources. In other words, the sequence as such does not cause any resource to become a bottleneck.*

(ii) *The ratio of the touch time to the production lead time is very small (less than 10 percent before S-DBR is implemented and less than 20 percent with S-DBR on). Touch time means the net processing time along the longest chain of operations. This definition is intended to exclude cases where assembly of thousands of parts, done on different sets of resources, might have a long processing time, but as the majority of the parts are assembled in parallel, the actual production lead time is not so long.*

The concept of S-DBR is introduced to offer simple but practical concept in both planning and execution of PPC. Unlike DBR, it has shifted away from detailed scheduling for any work centres. To better explain and further discuss the significance of the above necessity, the potential issues on S-DBR due to violation of the above assumptions will be discussed.

Issue on Re-entrant Flow

The first challenge to S-DBR is posed by sequence dependent production. This production process involves multiple re-use of CCR or re-entrant. The solution proposed by Schragenhem et al. (2009) and Chang and Huang (2014) is achieved by summing the processing time required for each re-entrant into *Plan Load* (PL) and *Production Buffer* calculation. The due date obtained will smoothen the work load in the system. In addition, the order release date will be adjusted according to the adjusted production buffer. However, this is only valid if the touch time is insignificant.

Issue on Long Processing Time

In S-DBR, as detailed scheduling and sequencing is not considered in both planning and execution stage, the protection on due date relies on the significantly lower 'processing time – lead time ratio'. Long processing time may evade or 'confuse' the function of buffer management. Due to the reduced responsiveness of the production system to recover from any uncertainties, it reduces the ability to protect due date (Goldratt, 2009; Schragenheim et al., 2009: 73).

For example, the total production time or a work order is ten days and requires five different work operations. If the last operation requires 40% of the lead time, by the time the work order arrives at this operation, it might be too late to recover from any slack. To overcome this, with the assumption that the long processing operating work centre is in the middle of the routing, it is used as a decoupling point. Schragenheim et al. (2009: 75) proposed the deployment of two buffers. The first buffer is placed before the long processing operating work centre. This is to ensure works arrive at the long processing time operation in time. The second buffer is to protect the overall due date.

In addition to long touch time, some MTO manufacturing environment produces one-offs products which requires significant iterative design and *trial and error*, such as precision tooling. The significant uncertainties involved resembles project environment. A separate solution to such environment is proposed by Scheinkopf et al. (2012): *Linear High Touch Time* and Inherent Simplicity (2010). In addition to the decoupling and dual buffer concept introduced by Schragenheim et al. (2009: 75), it is recommended to have more frequent feedback on order progress. To overcome the difficulty in quantifying work progress, percentage or ratio are proposed.

Issue on Wandering and Multiple CCRs

The issue of wandering bottleneck is a much-debated topic since the inception of DBR. Various improvements have been suggested to deal with *wandering bottleneck*. This is also referred to as *dynamic bottleneck* or *shifting bottleneck* by both TOC and WLC researchers (Carmo-Silva and Fernandes, 2017; Lawrence and Buss, 1994; Riezebos et al., 2003; Scholz-Reiter et al., 2011). In S-DBR, Scharagenheim et al. (2009: 65) highlighted the possibility of *creating* dominant CCR through management intervention, such as elevating a CCR through additional investment on capacity. Alternatively, the idea of multiple plan load monitoring is proposed.

3.3.8 Summary

Section 3.3 has discussed the MTO PPC solution developed and used by TOC practitioners. The evolution path shows that TOC practitioners move away from creating complex solutions for complex environment. Instead, they advocate solutions which are simple and flexible to protect against uncertainties. From OPT system, which originated from an *algorithmic* centric software seeking to produce *most feasible* schedules, to DBR, which advocates detailed scheduling only on the CCR ('philosophical layer'), to the recent S-DBR, which eliminates detailed scheduling altogether. It is a paradigm shift from detailed planning to the concept of simple (good enough) planning with empowerment given to shop floor on execution. Based on the above discussions on WLC and S-DBR, section 3.4 will provide a critical review on both solutions.

3.4 S-DBR and WLC

As discussed in Section 2.3, both S-DBR and WLC have been advocated as suitable PPC application for MTO manufacturing environment. This section will begin by providing an overview on the similarities and differences between the two systems, particularly from both conceptual and design level. This is followed by viewing S-DBR through the WLC lens.

Both PPC solutions adopt systemic approach in dealing with production flow. Shop floor is regarded as an input/output system, where input to a system is controlled in accordance to the system output. To smoothen and increase flow, various control points are introduced to reduce WIP and increase production throughput. Although both PPC solutions share similar systemic approach and objectives, they utilise different mechanisms to achieve the objectives.

Planning and Execution

WLC advocates relatively heavier emphasis on *planning* (thus more complexity), which in return requires simpler effort in *execution*. On the contrary, S-DBR, having evolved from a relatively more complexed OPT system, emphasises simplification in *planning* stage, allowing relatively more emphasis in *execution* stage. Acknowledging that the environment is dynamic, the objective in *planning* is to provide a *good enough* guide, with the emphasis not to be more accurate than the *noise* (Goldratt, 2009; Schragenheim, 2010:230). Emphasis is placed on developing a flexible and responsive system in the *execution* stage to react to uncertainties and variation. This includes empowering management and shop floor personnel to make decision based on contextual environment.

This concept is also evident in the LUMS WLC approach where a relatively simple load aggregation rather than the more complex probabilistic method is adopted in the planning stage. It is worth noting that both WLC and S-DBR avoid using complicated job sequencing algorithm to dictate shop floor personnel. However, S-DBR explicitly acknowledges the importance of *tacit knowledge*, where shop floor personnel are empowered to utilise both *tacit knowledge* and S-DBR information in dealing with uncertainties (refer to Element number 4.11.2 in generic S-DBR S&T in Harmony, 2017; Hendry and Kingsman, 1991).

Focus

Inheriting from TOC philosophy, S-DBR emphasises the concept of being *focus*. Improvement effort is focused on the key requirements that are clearly critical to the systemic improvement. It is essential to protect these key requirements against uncertainties (Schragenheim, 2010:234). Through the five focusing steps, *constraint* within a system is targeted for incremental and continuous improvement. In S-DBR, by recognising *market* as the ultimate *drum* to set the pace of the system, all work centres are aligned towards a similar systemic goal of achieving due date adherence through buffer status. Only work centres with potential of turning into CCR are monitored. This simplifies the development and deployment of a PPC in a company, particularly for SMEs.

In WLC, managing between the concept of *work load balancing* and the requirement of *due date adherence* in an MTO environment is a *dilemma*. As highlighted by Land (2004), depending on situation, *load balancing* and *due date adherence* could either be friends or foes. The concept of load balancing is to ensure work centres perform as closely to workload norm as possible. This is to ensure *accurate* and *stable* throughput time, which in return results in due date adherence. However, the strict rule of keeping work centres close to its workload norm, or to keep work centre busy at all time, has the possibility of causing less urgent jobs to be pushed for completion instead of the urgent jobs. The emphasis on having accurate throughput time assumes an ideal and static environment, which is contextually dependant.

While workload norm explicitly limits WIP, it is not explicit on the availability of buffer capacity to be deployed for *due date adherence*. It is also unknown whether the activation of additional capacity will have adverse effect towards the centralised workload balancing designed. A practical shop floor is dynamic with uncertainties such as machine breakdown. This makes the reliance on absolute throughput time at work centre impractical. From the discussion above, the use of workload balancing is a thin line between achieving *local optima* (keeping resources busy) and *systemic throughput* (due date adherence).

Dealing with Uncertainties and Variation

The third aspect to be discussed concerns the acknowledgment on the existence of variation and uncertainties in MTO manufacturing environment. Both approaches adopt the concept of buffer to protect against variation and uncertainties, albeit being deployed in different ways. In WLC, the concept of pooling, by avoiding immediate release of work order onto the shop floor provides buffer to protect against uncertainties such as changes to orders. In addition, WLC buffer work centres with queue of work orders to avoid starvation. By adopting workload balancing, work centres are configured to operate at workload norm capacity (by controlling both capacity and queue length). In the original concept of WLC, the lack of explicit use of buffer to protect due date adherence against uncertainties lack practicality. This is evident with the recent inclusion of buffer-time in the calculation of both pool-waiting time and throughput-processing time for due date adherence (Thurer et al., 2017a). In addition, the researchers also acknowledge the need to have order release date integrated with due date setting in the PPC design. Although buffer is deployed in different ways, to a large extend, both PPC solutions share similar objective of protecting delivery date against variation and uncertainties.

Rules in WLC

In WLC, various *rules* have been introduced, mixed and matched to find the *best fit* through simulation. The rule categories researched mainly centred around two key elements: *System Loading* and *Due Date Adherence*. These elements are also the focus of S-DBR: *Plan Load* and *Buffer Management*.

The remainder of this section will explore S-DBR under WLC rules. Based on the categorisation of WLC rules used by Bergamaschi et al. (1997), Fredendall et al. (2010) and Stevenson (2006), the following rule categories will be used for subsequent discussion:

(i) Order release mechanism,
(ii) Workload consideration,
(iii) Priority dispatching, and
(iv) Capacity planning and visualisation.

3.4.1 S-DBR Order Release Mechanism

Informed decision makings at all control points are only achievable through the work load information feedback obtained from shop floor. Order release concept in S-DBR/DBR/OPT has often been generally referred to as *bottleneck* mechanism in WLC research (Roderick et al., 1992; Bergamaschi et al., 1997) or *theory of bottleneck* in operations management (Boer et al., 2015). While the concept of *bottleneck* has been introduced in practitioner world through OPT in late 1970s, in WLC, it was first introduced as a job release mechanism known as '*Starvation Avoidance*' by Glasse and Resende (1988). Since then, attempts have been made to compare *bottleneck* based DBR and *aggregate* based WLC.

Using conceptual arguments, Fry (1990) argued that in the event where there exist a significant bottleneck within a system, performance of DBR is more significant. However, in the case where there is no significant bottleneck, WLC will outperform DBR. This conceptual argument is further supported by Roderick et al. (1992) through simulation, where DBR shows a better performance.

Both TOC and WLC input-control methods have been described by Enns and Prongue Costa (2002) as the *Bottleneck Strategy* and the *Aggregate Strategy*. In their study of input control, two perspectives were proposed: *Capacity Constrained* or *Market Constrained*. If market demand is higher than internal resource capacity, the scenario of *Capacity Constrained* happens. *Market Constrained* happens if internal capacity is higher than market demand. Under *Capacity Constrained* scenario, release is controlled by monitoring the bottleneck loading. Whereas in *Market Constrained* situation, shop load is to be monitored. This perspective is in-lined with the assumptions used in DBR and S-DBR. In DBR, the assumption is that market demand is higher than internal resource capacity. However, as argued by Schragenheim and Dettmer (2000), market is normally the dominant constraint, and proposed the use of S-DBR.

In the simulation study performed by Enns and Prongue Costa (2002), it is found that '*Bottleneck Strategy*' out performs '*Aggregate Strategy*' in high routing variability shop floor. Their simulation demonstrated better performance if a priority dispatch rule is assigned. For example, higher priority is given for works which requires higher processing time at bottleneck resource. However, in their research design, orders which does not require bottleneck resource are released immediately onto the shop floor. This design results in high WIP for non-bottleneck resources.

In the above discussed researches, DBR concept has been largely simplified and reduced to a '*bottleneck*' rule, which in a loose way, only refers to the '*Constraint Management*' part of the DBR solution. With the '*Buffer Management*' part of the solution ignored, simulation based MTO PPC performance comparison studies conducted might have overlooked the potential of TOC based solution.

In S-DBR, *Market* is assumed to be the ultimate constraint within the system. This places a 'long rope' in between the 'constraint' and the 'entrance' into the system. Order release priority for all accepted work orders are determined using '*Buffer Management*' concept, which is based on the ratio of remaining touch time and time available from now till promised delivery date, also known as '*Buffer Status*'. Work orders having a due date larger than the buffer time are not to be released into the system.

As described by Bergamaschi et al. (1997), there are two major types of order release mechanisms: *load limited* and *time phased*. The load limited approach releases orders based on existing workload on the shop floor, which allows direct control of WIP inventory. As for the time phased approach, it releases orders based on the predetermined time computed from information such as due date, work content and routing. From the above description, S-DBR falls under '*time phased*' as the total touch time (actual time a product is worked on) of a work order is determined based on both work content and necessary routing. Putting into MTO context, high due date performance is regarded as one of the 'order winning criteria' (Stevenson et al., 2005; Goldratt and Cox, 1984). Thus, releasing work orders into a system 'in-time' is critical. However, adopting this release approach without considering shop floor loading will cause high WIP in the system, which in turn will cause reduced due date performance.

While 'time' is being monitored in S-DBR, the potential capacity constraint work centres are simultaneously monitored using '*Load Management*'. On the one hand, it is to ensure due date to be fulfilled, and at the same time allow intervention from higher management if unexpected events occur at capacity constraint work centres. Work load measure in S-DBR is in work quantity, where work being loaded is expressed in time (touch time) and converted into percentage to facilitate *Buffer Management*, where work orders will be prioritised, expedited, feedback, and targeted.

In WLC, there are two categorisation of timing convention: discrete and continuous. Discrete refers to periodical release, for example, daily or weekly. Continuous timing is more fluid, which arguably allows *real-time* and flexible response to the dynamic MTO environment (Stevenson, 2006). S-DBR adopts continuous timing convention. However, in execution, this could be a contextual dependent decision.

Considering practical constraints, Schragenheim et al. (2009) suggested daily *re-plan rate* where new orders and work completion is updated daily. With the advancement of computer hardware, continuous close to *real-time response* can better support decision making in all control points (Huang, 2017). Due to practical consideration, this might be physically executed on daily or weekly basis.

In a recent development in LUMS based WLC, using theoretical arguments and simulation, Thurer et al. (2017a) have proposed the integration of planned release due dates with due date setting procedures. Instead of releasing jobs periodically into the system, they proposed the release of jobs into the system according to the planned release dates when due date was initially set. To deal with the concern where such release mechanism might cause overloading or starvation for work centres, finite loading and starvation avoidance mechanism are suggested to be deployed.

Through simulation, this proposed approach shows significant improvement in throughput time and tardiness reduction. This discovery has prompted the researchers to call for a paradigm shift. Instead of considering due date setting and order release as two independent decision levels, both are proposed to be considered in a single integral procedure during due date setting. This paradigm shift discovery coincides with the approach in S-DBR, where both *Constraint Management* and *Buffer Management* are used.

3.4.2 S-DBR Workload Consideration

Underpinned by TOC concept, system throughput is determined by the CCR within an unbalanced system. Through the focusing steps, only the work load of potential CCR work centres will be closely monitored. As illustrated in previous sections, in MTO, fulfilling due date promised is critical. This is achieved by monitoring potential

CCR through *Load Management*. Through *Load Management*, reliable due date can be provided before an order enters system. This is done through appropriate intervention such as due date renegotiations or deployment of additional capacity to meet due date commitment.

In view that S-DBR approach focuses only on capacity constraint work centres, it is considered a *bottleneck load* from the perspective of WLC. At the selected capacity constraint work centres, the touch time of all firmed orders to be processed at the work centre are aggregated without differentiating whether it is *in transit*, *released load* or *load on hand* (Bechte, 1988). This approach is known as *atemporal* and is advocated for its simplicity and close to real-world workload approximation of work centres (Bergamaschi et al., 1997).

In S-DBR, there is an element of *probabilistic assumption* where parts will complete upstream processes and ready to be processed by CCR within half of the production buffer time. It is also assumed that the processes at CCR and all downstream work centres will be completed within half of the production buffer time.

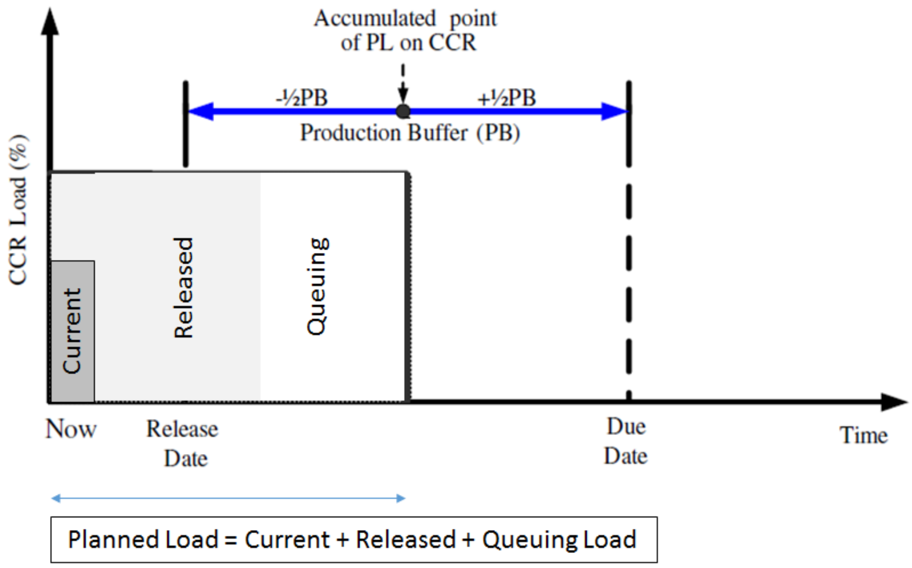


Figure 3.17: Planned Load expressed in WLC terminology

3.4.3 S-DBR Priority Dispatching

In WLC, workload norms setting, a workload boundary setting for each work centre, is a much-debated topic. As discussed by Stevenson (2006), this is a parameter setting which requires simulation, trial and error, as well as input from experienced shop floor personnel during practical implementation. The purpose is to achieve balanced workload. This setting is crucial to WLC as it ‘creates’ the ‘pulling force’ to move parts on the shop floor.

In contrast, S-DBR acknowledges the existence of unbalanced work centres on the shop floor. Underpinned by the objective of achieving systemic throughput rather than the optimal usage of all work centres. All confirmed work orders are prioritised, monitored and controlled by individual *Buffer Status*. Work orders are progressed between work centres through the *pulling force* exerted by *Buffer Status*. As capacity constraint work centres determines the system throughput, efforts are made to ensure these work centres operates at optimum level. All other work centres operate with *road runner* attitude, avoiding any *student syndrome*. Sequence of work orders at all work centres are aligned to the *Buffer Status*.

There are many benefits in the use of *Buffer Status*. First, work order prioritisation is easily observed through the colour codes (Schragenheim and Ronen, 1991). The *extra capacities* of non-capacity constraint work centres are exposed and can be used to protect against uncertainties and variabilities (Stratton, 2012). By having *Buffer Status* instead of a *detailed schedule* (with sequencing), it empowers shop floor personnel to make sequencing related decisions based on contextual requirement (Bernavides and Landeghem, 2015). Lastly, all work centres are aligned towards similar prioritisation, which is visible to both shop floor and non-shop floor departments.

3.4.4 S-DBR Capacity Planning and Schedule Visibility

According to the classification of Bergamaschi et al. (1997), WLC capacity planning is of two categories: active and passive. Active capacity planning system allows resource capacity to be adjusted during system operation. Passive capacity planning however does not allow any control to system output.

In S-DBR, it is desirable to have early detection and warning on potentially late work orders through its *Buffer Management* mechanism. The main purpose is to allow appropriate intervention to protect the delivery due date. The intervention includes activating excess capacity resources. Coupled with the use of *Load Management*, S-DBR arguably provides extended visibility to management personnel to manage with a systemic view and over a time horizon into the near future. Schedule visibility allows S-DBR to provide Sales Department the ability to request for a reliable order due date.

Underpinned by TOC philosophy, ‘time’ is explicitly deployed as buffer to protect work orders. However, unlike WLC, it does not include consideration of ‘potential work orders’ and ‘strike rate’ into work load calculation. The discussion above is summarised in *Table 2.4* using the eight categories of WLC rules adapted from Stevenson (2006).

3.4.5 Summary: S-DBR based WLC

From the above discussion, it is evident that although both WLC and TOC has distinct conceptual origin, S-DBR and WLC shares some similar thread with similar objectives. This is in-line with the call by researchers such as Fernandes et al. (2014) and Thurer et al. (2017b) for *cross-breed* research where salient features from each approach could be adopted. For example, the adoption of simplicity and practicality in the implementation of S-DBR solution. Under the broader research umbrella of WLC, as illustrated in *Figure 3.18*, it could be known as the S-DBR based WLC solution.

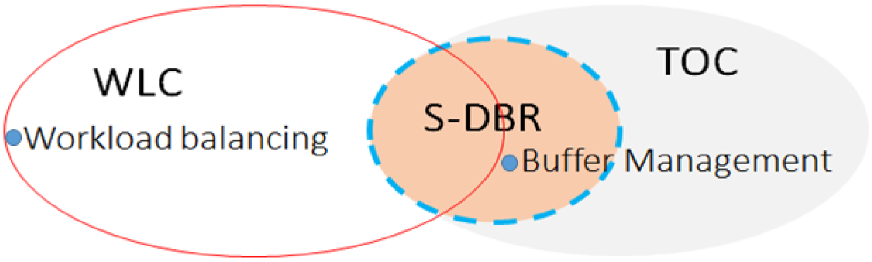


Figure 3.18: Position of S-DBR in WLC and TOC

Table 3.4: S-DBR from the Lens of WLC
Source: Adapted from Stevenson 2006

Dimension	**Options**	**Definition**	**Original LUMS Classification**	**Contemporary LUMS Classification**	**S-DBR**
Order Release Mechanism	• Load Limited • Time Phased	The mechanism can be either base upon a predetermined **time phased** released date or to satisfy shop floor **load limited** constraints	Load Limited	Load Limited	Hybrid: • Load Limited during enquiry and entry stage • Time Phased there after (With consideration of loading on potential capacity constraint work centres, normally 80-90% loaded)
Timing Convention	• Continuous • Discrete	Decides when an order can be released, either at **discrete** time set intervals or **continuously** at any appropriate time	Discrete	Hybrid	Hybrid (Schragenheim et al. (2009) used daily)
Workload Measure	• Number of Jobs • Work Quantity	A measure of the workload of the shop or company as a whole, where if job specifications vary it may be necessary to consider **work quantity** in hours of work and not merely the **number of jobs**.	Work Quantity	Work Quantity	Work Quantity
Aggregation of Workload Measure	• Total Shop Load • Bottleneck Load • Load by each work centre	How workload is calculated and whether it represents **load by each work centre**, in the **total shop** or at **bottleneck** resources. As routing and processing times vary, the need to move away from total shop load may increase.	Load by each Work Centre	Load by each Work Centre, including Load on Hand and Load Upstream	Load by Potential CCR work centre, including load on hand and upstream,

Workload Accounting Over Time	• Atemporal (aggregate load) • Time Bucketing • Probabilistic	An indication of how the workload is distribute over time, based on varying assumptions about the load in transit, using an **atemporal**, **probabilistic** or **time bucketing** approach.	Atemporal	Atemporal with probabilistic element	Atemporal with probabilistic element with the assumption that most jobs will arrive at potential CCR at half of PB time
Workload Control	• Upper Bound Only • Lower Bound Only • Upper and Lower Bounds • Workload Balancing	The method by which the released workload is regulated on the shop floor, based on **balancing** workloads across work centres, or using **upper**, **lower** or **upper and lower** workload bounds.	Upper and Lower Bounds	Upper bound with Unenforced Lower Bound and Optional Balancing by Supervisors	Monitored and dispatched by buffer status. Adopts ‘road runner ethic’, and at the discretion of supervisors
Capacity Planning	• Active • Passive	The ability to make capacity adjustments within the planning horizon, beyond the customer enquiry stage varies from **passive** to **active** participation	Active	Active	Active
Schedule Visibility	• Limited • Extended	The ability to look beyond the current planning period, considering future time period capacity requirements and customer orders. Aims vary from long-term shop performance (**extended visibility**) to a short-term present planning period perspective (**limited visibility**).	Limited	Hybrid	Hybrid

3.5 Suitability of S-DBR as PPC in MTO environment

In section 3.4, S-DBR is analysed alongside WLC. In the analysis, S-DBR is evaluated as a complete PPC concept and solution, beyond the common perspective of reducing it into a mere ‘bottleneck’ rule. It is found that there are various similarities between the two PPC approaches. In a wider sense, it could be considered an S-DBR rule based WLC. This section will continue to evaluate the suitability of S-DBR as a PPC in MTO environment.

Similar reviews have been conducted by Hendry and Kingsman (1989) and Stevenson et al. (2005) using theoretical argument and observation in practice. In the first review, OPT has been reviewed as not a convincing MTO PPC solution. This is mainly due to its lack of emphasis in capacity planning and delivery date determination in the customer enquiry stage. Rather, the emphasis is on increasing throughput or to meet a pre-set delivery date by exploiting the constraint within internal resources. In the second review, DBR has been criticised for its lack of involvement in the customer enquiry stage. In addition, the notion that a *bottleneck* is static might not be applicable to MTO where *wandering bottleneck* is more likely due to increase in routing variability. In both reviews, WLC is advocated as the most appropriate PPC solution in MTO environment.

The following evaluation criteria has been adopted in both reviews (Hendry and Kingsman, 1989; Stevenson et al., 2005):

(i) Customer Enquiry Stage for capacity planning and delivery date determination.
(ii) Job Entry and Release stages for due date adherence.
(iii) Ability to cope with non-repeat production
(iv) Ability to provide planning and control for variable shop floor routings
(v) Applicability to SMEs.

In 2009, Land and Gaalman explored the essential elements to be included in a PPC solution for MTO companies by identifying the problems faced by seven case companies. From the findings, the problems identified are found to be of relevance to these three stages: *order acceptance*, *order release*, or *shop floor dispatching*. This finding corresponds to the five evaluation criteria used in earlier reviews.

The *Order Acceptance* category corresponds to (i) where capacity planning and order due dates are determined. *Order Release* category includes both job entry and release for due date adherence identified in (ii). Criteria (iii) and (iv) are embedded in *Shop Floor Dispatching* where routings through shop floor is of concern.

With the assumption that *market* is the constraint, S-DBR explicitly subordinate all elements within system to *market*. The monitoring of *planned load* at potential CCRs is designed to determine delivery date and capacity planning. The use of buffer management explicitly assigns *buffer status* to each work order at *job entry stage*. Through *buffer status*, order release and dispatch control are explicitly aligned and paced according to due date. With the simultaneous monitoring of *planned load*, early warning on potential CCR enables management to discuss and take necessary action to smoothen the flow proactively. As demonstrated by Schragenheim et al. (2009) and Chang and Huang (2014), each order is monitored both individually through its *buffer status* and *production buffer*, and collectively through load management, variable shop floor routings can be effectively planned and controlled.

As a solution conceived by the TOC practitioner community, the fundamental concept and building blocks of S-DBR are relatively simpler than its predecessors: OPT and DBR. It has moved away from detailed scheduling, introduced simple logic behind parameters, requires minimal information from ERP system (minimal integration), and provides visible and simple priority dispatch signals (Benavides and Van Landeghem, 2015; Hwang et al., 2011; Schragenheim et al., 2009).

From the above discussion, S-DBR is advocated as a suitable PPC solution in MTO environment for SMEs. As part of this research, its applicability will be further explored through its actual implementation in an SME company. To facilitate the PPC implementation, particularly in SMEs, it is necessary to review the challenges identified in existing literature to inform this research. This will also act as a basis to further capture any additional knowledge generated throughout the PPC implementation process. The next section is devoted to highlight the issues and challenges faced in the implementation of PPC in MTO environment, with focus on WLC and S-DBR.

3.6 Challenges faced in MTO PPC implementation

In search of a guide to inform the implementation of S-DBR based PPC, this section will begin by reviewing the implementation issues faced by WLC. This is relevant as WLC is being advocated as the most relevant PPC solution in MTO environment (Stevenson et al., 2005). Given that there are limited academic publication regarding S-DBR, the three journal articles, which discuss real case S-DBR implementation, will be reviewed to identify implementation issues highlighted. The above reviews from both WLC and S-DBR will be consolidated and used to inform the implementation of S-DBR in this research. Although WLC has received large attention from researchers, the focus has been on conceptual and simulation with limited successful industry implementation reported (Hendry et al., 2008; Romero-Silva et al., 2015; Thurer et al., 2011).

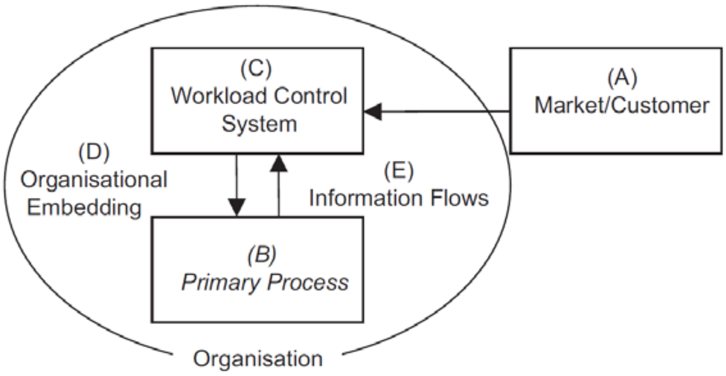


Figure 3.19: The five categories used to classify WLC implementation issues
Source: Hendry et al. (2008)

With the aim of proliferating WLC in practice, Hendry et al. (2008) has proposed a framework to analyse and capture any implementation related knowledge generated. This framework was subsequently used and enhanced through subsequent WLC implementation case research by Hendry et al. (2013). In the earlier research, Hendry et al. (2008) reported seventeen implementation issues and categorised them into five categories as shown in *Figure 3.19.* An additional three issues were identified in the later research as shown in *Table 3.5*.

With reference to *Table 3.5*, the issues highlighted can be broadly categorised into *PPC system* related, *People* related, and *Technology* related. These are similar to the issues captured in the three S-DBR implementation related journal articles (Allison et al., 2012; Bernavides and Van Landeghem, 2015; Huang et al., 2011). Implementation issues which are S-DBR specific, such as assumption used, has been discussed in section 3.3. Apart from category A, B, and C, issues in both D and E are related to *people*. The remainder of Section 2.6 will review the role of *people* in PPC implementation.

Table 3.5: Key implementation issues in WLC
Source: Adapted from Hendry et al. (2008; 2013)

Category	**Key implementation issues**	**Example**
A. Market/ Customer Characteristics	A1. Characteristics of order quotations	Unspecified or unrealistic DDs
	A2. Uncertainty at the customer enquiry stage	Effect of long delays between a customer enquiry and order confirmation on workload calculations
	A3. Rush orders	Orders sometimes have greater urgency
	A4. Seasonality and volume growth	Seasonal demand and/or step changes in demand
	A5. Hybrid production	Mainly MTO, but some stock items
B. Primary process Show complexities that have not been considered in the design of the WLC concept previously	B1. Assembly requirements	Release decisions for separate parts which converge for assembly processes
	B2. Sequence dependent setup times	Workload calculations when there are sequence dependent set-ups
	B3. Alternative shop floor routings	Grouping machines to allow flexibility of capacities
	B4. Industry-specific process	E.g. Oven process that require batching
	B5. Uncertainty after the order release stage	Changing customer priorities that require some orders to be delayed in favour of new orders
C. WLC system Includes certain conceptual aspects, which appear not to have been adequately developed	C1. WLC-related start-up issues	Making an effective transition from current practices including long lead times to new ways of working, by changing the WLC parameters over time
	C2. Incomplete routing data at customer enquiry	Making appropriate DD assignment decisions when the routing information available is incomplete
	C3. Time-span-dependent critical resources	Bottlenecks that can change between the customer enquiry stage and the job release stage
D. Organizational embedding Includes new issues regarding the embedding of a WLC concept within an organisation, which emerged at the implementation phase	D1. Awareness of the concept of WLC	Education needed for the workforce in the WLC concept as initial awareness low
	D2. User visibility	Balance between providing easily understandable information and sufficient of the underlying WLC logic to ensure WLC is appropriately used
	D3. Support of task structures	Integrating the WLC concept with current tasks, such as providing support for decisions involving both planning and sales
	D4. End-user choice and involvement	Appropriate selection of the end-user for each stage of the WLC process

	D5. Accommodating functionality requests	Ensuring that additional functionality requested does not conflict with the WLC concept
E. Information flow Includes solutions affecting WLC approach, required to enable information flow, both into and out of the WLC system and control the shop system and control the shop	E1. System-related start-up issues	Finding effective ways to fill the database at the onset of the project
	E2. Integration with other systems	Integration of the WLC system with existing ERP or other database systems

3.6.1 The role of *people* in PPC implementation

With the advancement in technology, PPC concepts can be realised by embedding scheduling heuristics and algorithms in computer-based devices. However, ignoring *human factors* in the development of PPC is a critical omission (Crawford, 2001; McKay, 2001). As described by Goldratt (1988), "…*Computerized shop floor scheduling is just a small issue in the much broader problem of successfully running a manufacturing company*…". While it is acknowledged that PPC fundamentally utilises mathematical models to substantiate rational decision-making and system optimization, it is argued that these generalised algorithms are not necessarily applicable in all ostensibly similar environments (Brocklesby, 2016; Mokotoff, 2001; Strohhecker et al., 2016).

Although both PPC (with its underpinning theoretical approach) and *people* (practitioner) make scheduling decisions, PPC merely makes decision based on relatively simple quantitative measures and algorithmic procedures (Higgins, 2001). Problems encountered on the shop floor are not discrete nor static and cannot be solved by optimising algorithms on their own. Rather, the problems are *dynamic processes* which requires *people* to manage them over time.

Researchers also found that increase in complexity in manufacturing environment requires increase human intervention (McKay and Wiers, 2001; Nakamura and Salvendy, 1994). As highlighted by Nakamura and Salvendy (1994), other than the contextual manufacturing environment, the complexity also refers to the algorithm in

PPC. This is supported by Fransoo and Wiers (2008) who found positive correlation between complexity in environment and tendency of human neglecting PPC.

From the perspective of *people*, the decision-making process is a social activity, an interaction of complex values and goals within the system of people which might affect themselves. As described by MacCarthy and Wilson (2001), ultimately, it is the *people* who run the shop floor, make things happen, and reap the fruit of their work. As *people* is the ultimate recipient of the decision made, it is argued that PPC is perceived as successfully implemented if it provides positive benefits to *people*.

In view of these, it is necessary to develop PPC into a *tool* to assist *people* in making decisions. It is no longer a debate on whether PPC or *people* is a better *planner*. Rather, it is necessary to acknowledge the complementary roles of both *people* and *PPC* (Berglund and Karltun, 2007; Van Wezel et al., 2011). This is supported by calls to develop PPC into a decision support system (DSS) with the inclusion of human role (Arica et al., 2016; Fransoo and Wiers, 2008; Higgins, 2001; Jackson et al., 2004; McKay and Buzacott, 2000).

In general, DSS is a computer-based solution which provides *processed information* based on input information (data) and pre-defined logics and algorithms (Laudon and Laudon, 2002; Shim et al., 2002). However, the suggested decisions by DSS based on *processed information* is only valid for *structured* part of the problem. The *unstructured* part of the problem has to rely on *people*, which forms the *people-system* partnership (Klein and Methlie, 1990; McKay and Wiers, 2006). According to Norman (1988), *structured* problem refers to tasks which are *laborious* or *repetitive* whereas *unstructured* problems involves uncertainty and unfamiliarity. The generic characteristics of WLC based DSS developed is summarised by Stevenson (2006) into the following:

(i) Ability to support regular decision making. Decisions varies according to contextual environment.
(ii) Ability to allow user intervention and control.
(iii) Allows simplified and quick decision-making process across the hierarchy.

Human role has been explored by Jackson et al. (2004) through empirical study. In this study, three common roles of *people* in PPC have been identified:

(i) Interpersonal role: “*developing interpersonal networks, informal bargaining, friendship and favour network and mediation*”.

(ii) Informational role: “*as information hub, filtering information to the shop floor, and ensuring that information is accessible and visible*”.

(iii) Decision making role: “*problem prediction and problem solving, interruption handling, and resource allocation*”.

The *people* in their research refers specifically to *Production Manager*. To effectively support the development of PPC into DSS, based on both theoretical argument and empirical research, a guideline with four design aspects is proposed (Wiers and van der Schaaf, 1997; Wiers, 2001). These aspects are:

(i) level of support,
(ii) transparency,
(iii) autonomy, and
(iv) information presentation.

Details of each design aspect is discussed as follows.

Level of Support

Instead of seeing PPC as a potential threat of replacing *people* (Tarafdar and Gordon, 2007), it is necessary for PPC to support *people* rather than the other way around (Higgins, 2001; McKay, 2001). This requires a *sharing* of responsibility between *people* and DSS. It is suggested that proper division of functions between the two can improve worker empowerment, quality leadership and human coordination (Slomp, 2001; Wilson, 2003). To achieve this, researchers suggested the identification of routine and non-routine elements on shop floor (Fransoo and Wiers, 2006; Mckay and Buzacott, 2000). With this, DSS is anticipated to process routine tasks which require manual skills and abilities. Humans would focus on tasks which requires tacit knowledge and mental interpretive skills and abilities (Slomp, 2001).

Transparency

As described by McKay (2001), the tool has to reflect the contextual problem in hand. In addition, the logic (or assumption) used by DSS to arrive at proposed decision has to be simple enough for *people* to intuitively understand. It should not create additional complexity for the users (Gasser et al., 2011). To avoid falling into the trap of complexity, Wiers (2001) encourages the active involvement of *people* in co-developing the algorithm. As highlighted by Crawford (2001), this is a challenging process. It includes the capturing of *tacit knowledge* hidden within the daily routine of *people*, filtering and analysing them, before converting the generic patterns into heuristic algorithms to support DSS decision making. Although it is challenging, this process is necessary for the development of *trust* in *people* towards the DSS developed. *Mistrust* and *distrust* by *people* on DSS will have costly implication on business performance (Lee and See, 2004; Muir and Moray, 1996). According to Muir and Moray (1996), *trust* in *people* is determined by their perception of the system's competence. Their study also shows that any incompetence in the system directly reduces *trust* within *people* even though the incompetency has no effect on the overall system performance. Repeated perceived infeasibility of DSS will cause DSS to be ignored by *people* (Kleinmuntz, 1990).

Autonomy

As a decision supporting tool, it needs to support the activities within the individual's area of autonomy, so enabling them to take control in making decisions (McKay, 2001). This involves higher management clarifying the boundaries associated with the management role at various (both vertical and horizontal) control points within the company's business process flow (Harvey, 2001).

Information Presentation

As described by Wiers (2001), this is a *key factor* of an effective human-computer interaction consisting of *what* and *how* information is presented to *people*. In addition, it includes the human-computer interface, leading to human-computer interaction. Information presentation is to guide, stimulate, and advance *people's* decision-making capabilities over time without interfering with their perception (Higgins, 2001). A combination of textual (suitable to display low aggregation level information) and graphical (suitable to display high aggregation level information) presentation are used according to contextual requirement (Wiers, 2001).

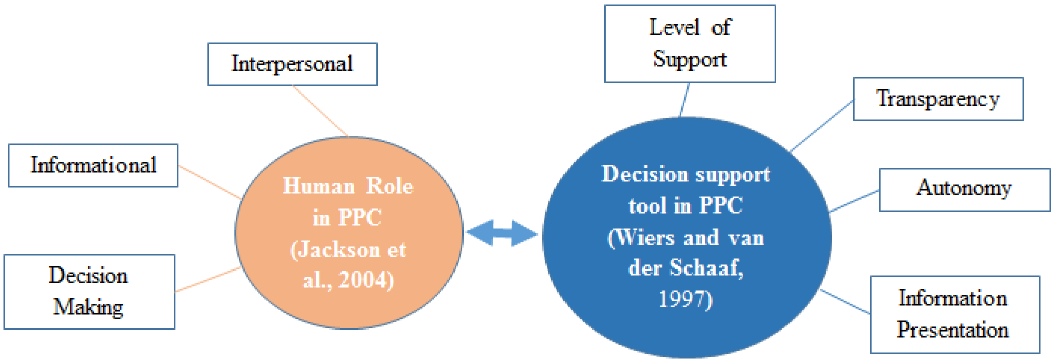


Figure 3.20: Human roles (HR) and DSS Design Elements for PPC

Table 3.6: Proposed HR-DSS framework to implement a DSS for Amberol

		Decision Support System (DSS)			
		Level of Support	Transparency	Autonomy	Information Presentation
Human Role (HR)	Interpersonal				
	Information				
	Decision Making				

The discussion in this section highlights the importance of *human role* in the development of PPC solution into a decision support system. With the aim to provide a better guidance throughout the development of S-DBR into a decision support system, a taxonomy is proposed by crossing both *human role* (HR) and DSS design elements in PPC. The resulting *HR-DSS* matrix is shown in *Table 3.6*.

It is proposed that this matrix potentially able to highlight the necessary consideration in developing DSS according to each *human role* identified. For example, the developed DSS system must support the *Interpersonal* human role of the production manager. This is further analysed by looking into how the elements of *Level of Support*, *Transparency*, *Autonomy*, and *Information Presentation* contributed towards *Interpersonal* role. Similar analysis is conducted on the two other identified human roles: *Information* and *Decision Making*.

3.7 Performance measurement for MTO PPC

Although there are limited reported empirical research conducted on S-DBR, a comprehensive performance measurement review on S-DBR has been conducted by Benavides and Van Landeghem (2015). Performance measurement used by both DBR and S-DBR are included in their review. The performance measurement used are divided into four categories: Time related, Dependability, Shop load measures, and Financial-related measures. In a review conducted on performance measures used in WLC research, other than the four categories highlighted above, three other categories of performance measures are used: market related, internal/external co-ordination, and any qualitative evidence available to support the claim that improvements are linked to the use of WLC (Hendry et al., 2013). Some examples of performance measurements used by both WLC and S-DBR are summarised in *Table 3.7*. These performance measurements serve only as an indicator and guide to continuously improve the PPC developed and deployed. As highlighted by McKay and Wiers (2006), providing feedback on performance may be counterproductive. This is due to the over-zealousness in competency evaluation rather than to increase competency (Johnson et al., 1993).

Table 3.7: Examples of Performance Measurements according to Category

Category	Measures
Time related	Mean cycle time, Standard deviation of cycle time
Dependability	Mean earliness, Due Date Performance, Mean tardiness, Maximum tardiness, Quality
Shop load	Utilisation CCR, Resource utilisation, Location of the CCR, CCR production rate, Production daily rate, Productive capacity
Financial related	Throughput, Operating expenses, Sales volume, Profitability, Inventory cost
Market related measures	Proportion of rejected orders, Strike rate
Internal/external coordination	Coordination between production and marketing
Any other qualitative evidence	

3.8 Conceptual Framework

Based on the discussions in Chapter 1 and the prior sections in this chapter: Section 3.1 to 3.7, a conceptual framework is constructed for this research. As shown in *Figure 3.21*, the outermost layer shows the manufacturing environment under research: Make-To-Order (MTO). Based on the potential solution to the problem raised by the company through KTP, the second layer depicts the area of interest in this research: the design and implementation of production planning and control (PPC) system.

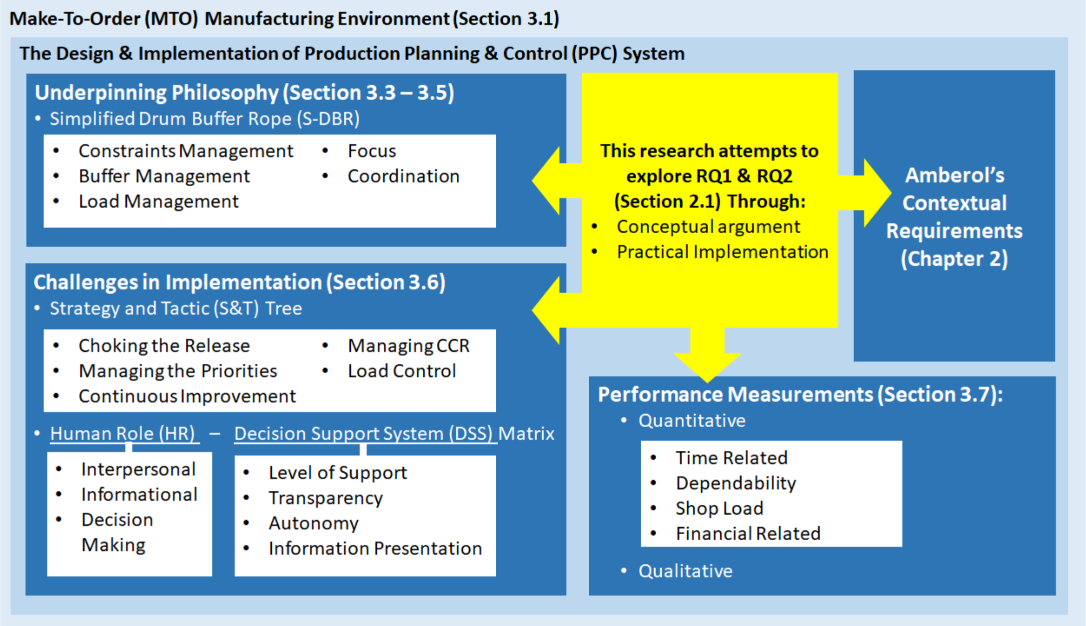


Figure 3.21: Conceptual Framework and Position of this Research

Within this area of interest, *fit* must be achieved between four critical aspects: *the underpinning philosophy*, *the challenges in implementation*, *the performance measurements to evaluate implementation*, and *the contextual requirements*. In this research, the underpinning philosophy to be researched is Simplified Drum-Buffer-Rope (S-DBR). Based on the understanding of S-DBR and the contextual requirements of the case company, answers to research question (RQ) 1 can be further explored through theoretical and conceptual arguments.

It is the interest of this research to further explore RQ1 through implementation. This constitutes the third critical aspect within the conceptual framework. The S-DBR implementation guide used by practitioners, known as the S-DBR Strategic and Tactic (S&T) tree, will be adopted. Based on academic publication, a matrix is developed by crossing human roles (HR) and decision support system (DSS). Both have been separately highlighted as crucial in the implementation of PPC. Through this proposed matrix, other than the *hard* side of PPC, it is anticipated that the *people* or *soft* side of PPC design and implementation can also be captured. It is the purpose of this research to capture the knowledge generated through the design and implementation of an S-DBR based PPC system in the contextual environment of the case company.

The final critical aspect in the conceptual framework developed is the performance measurements to be used to evaluate the implementation (section 3.7). In addition to the common use of quantitative criteria, qualitative results will also be used to evaluate the implementation.

3.9 Chapter Conclusion

In this chapter, through literature review and theoretical arguments, it can be concluded that S-DBR, evolved from its predecessor: DBR, is a suitable PPC for MTO. Other than inheriting the core concepts of Constraint Management, Load Management and Buffer Management from DBR, it explicitly emphasises customer enquiry stage with further simplification in its implementation.

Although both WLC and S-DBR has different origin and philosophical approaches, stripping WLC off its complicated rules bears resemblance to S-DBR. In contrast, by adding various rules onto S-DBR, it will resemble WLC. Both approaches focus on the improvement of systemic flow. To ensure stable flow, both systems acknowledges the need for *pool and ORR* (in WLC) or *choke and release* (in S-DBR) according to system throughput capacity.

In WLC research, various mechanisms in terms of rules have been explored through simulation. However, as highlighted by WLC researchers, there is a need for more empirical studies via actual implementation. For S-DBR, which has its origin from TOC practitioners, advocates simple solution in a complex world.

Table 3.8 summarises the findings based on the scope and objectives of this literature review laid out in the beginning of the chapter. This answers research question 1 and laid a foundation to answer the exploratory research question 2 via the actual implementation of S-DBR. Based on the above reviews, a conceptual framework is developed to underpin this research. The details on the design of this research and its implementation will be discussed in Chapter 4.

Table 2.8: Summary of Key Findings in Literature Review

Section	Literature Review	Summary
3.1	Reviewed the most appropriate PPC applications for MTO by academic researchers.	WLC has been advocated as most appropriate, whereas DBR has been evaluated as inappropriate.
3.2	Review WLC, the PPC evaluated as most suitable for MTO manufacturing environment, particularly in academia	Having diagnosed using the four planning levels and three control points. S-DBR is able to fit under WLC as a broad research umbrella. Proposed to be called S-DBR based WLC under the broader WLC research umbrella.
3.3	Review S-DBR, the latest PPC advocated by the TOC practitioner community yet received relatively low attention by researchers in academia	
3.4	Critically review the similarities and differences between WLC and S-DBR	
3.5	Review suitability of S-DBR as a PPC in MTO environment using criteria proposed by Stevenson et al. (2005)	S-DBR is a PPC solution suitable for MTO environment.
3.6	Review the challenges identified in the implementation of PPC, particularly from the WLC literature.	There are three key categories of implementation issues: PPC concept, people, and technology. These have been captured in the proposed human role (HR) – decision support system (DSS) matrix developed
3.7	Review performance measurements used in both WLC and S-DBR research	There are seven categories of performance measures which could be used to evaluate the performance of PPC implementation in MTO. These could be categorised into quantitative and qualitative measurements.
3.8	Construction of a Conceptual Framework to analyse the *fit* between *contextual environment* and *best practice.*	A conceptual framework is constructed to answer RQ1 and RQ2.

Table 3.9: Journal Articles which Compares WLC and TOC

Title	Author	Journal	Year	Research	Focus of Study	Result/Remarks
Controlling Input: The Real Key to Shorter Lead Times	Fry, T. D.	The International Journal of Logistics Management	1990	Conceptual	Comparing how JIT, DBR and WLC used input control to reduce WIP and manufacturing lead time	
A comparison of order release strategies in production control systems	Roderick, L. M., Phillips D. T., and Gary L. H.	International Journal of Production Research	1992	Simulation	Comparing ConWIP, Bottleneck, Production completion over time period, and Pre-determined level of production output	ConWIP and Bottleneck shows more superior results than WLC
Capacity-based order review/release strategies to improve manufacturing performance	Philipoom and Fry	International Journal of Production Research	1992	Simulation	To compare the impact of order review strategies to determine order rejection decision: (i) Total workload, (ii) Path load order review (similar to DBR)	Path load based order review is more effective.
An evaluation of capacity sensitive order review and release procedures in job shops	Philipoom, P.R., Malhotra, M.K., and Jensen, J.B.	Decision Sciences	1993	Simulation	Path based bottleneck (PBB) ORR is proposed and tested	PBB in practice may be simpler than traditional release-date based ORR
Order Release in Automated Manufacturing Systems	Lingayat, S., Mittenthal, J., and O'Keefe, R. M.	Decision Sciences	1995	Simulation	Compare different order release mechanism (ORM) under three different automated manufacturing environment	Bottleneck workload shows better results in shop floor with dominant bottleneck resource.
The effectiveness of input control based on aggregate versus bottleneck work loads	Enns, S. T., and Costa, M. P.	Production Planning & Control	2002	Simulation	Compare effectiveness of order release based on 'Aggregate Strategy' and 'Bottleneck Strategy' with assumption capacity exceeds throughput requirements	When work flow complexity increases, bottleneck input control out perform Aggregate input control.

						Note: Non-bottleneck jobs are released onto shop floor immediately upon arrival
Improving a practical DBR buffering approach using Workload Control	Riezebos, J., Korte, G. J., and Land, M. J.	International Journal of Production Research	2003	Empirical	Applying WLC order acceptance rules to improve DBR	Aggregate loads used on both potential CCRs to determine order release and to quote delivery date.
Aggregate load-oriented workload control: A review and a re-classification of a key approach	Stevenson, M., and Hendry, L. C.	International Journal of Production Economics	2006	Concepture	Review two important WLC element: (i) Loading measurement (Aggregate and Bottleneck Loading), and (ii) Workload norm determination	
Workload Control in Unbalanced Job Shops	Fernandes, N. O., Land, M. J., and Silva, S. C.	International Journal of Production Research	2014	Simulation	- Compare DBR and WLC in unbalanced work centres - How level of protective capacity influence WLC performance and its impact on setting workload norm	Both DBR and WLC out perform each other under different system settings. Workload norm settings is critical towards the performance of WLC. DBR functions well when there is a significant bottleneck within the system. However, it does not perform as well when there exist ‘wandering bottleneck’.
Drum-buffer-rope and workload control in High-variety flow and job shops with bottlenecks: An assessment by simulation	Thurer, M., Stevenson, M., Silva, C., and Qu, T.	International Journal of Production Economics	2017	Simulation	Compare DBR and WLC Order Release Mechanism	DBR performs better if a strong bottleneck exist. However, WLC outperforms DBR otherwise.

Chapter 4: Research Methodology

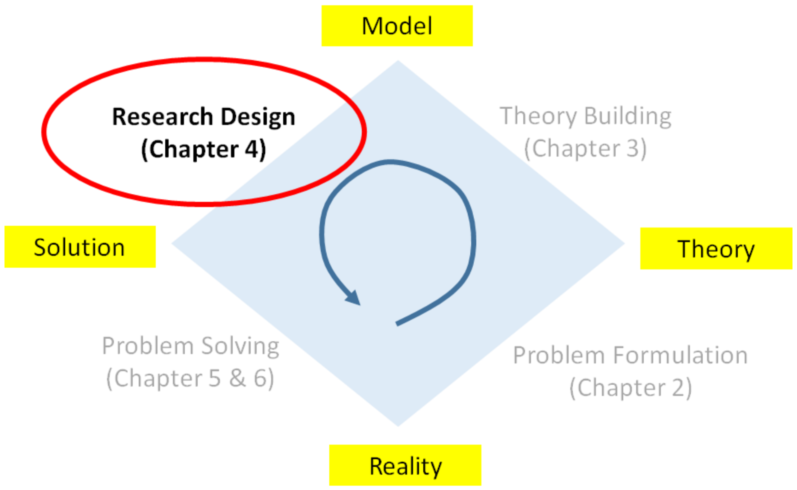


Figure 4.1: Organisation of this Thesis

Source: Adapted from Van der Ven (2007:10)

4.1 Overview

Chapter 3 has critically reviewed the applicability of Simplified Drum-Buffer-Rope (S-DBR). In addition, it has reviewed Production Planning and Control (PPC) implementation related issues and challenges. This has partially addressed the research questions set out in chapter 2:

> ***RQ1:*** ***What are the concepts underpinning S-DBR and how can they be configured to meet specific MTO contextual environments?***
>
> ***RQ2:*** ***What are the implementation issues in S-DBR and how may they be addressed?***

To further address the research questions, this chapter aims to determine the most appropriate research approach to be used. This discussion is separated into two major parts. The first part of this chapter focuses on evaluating and arriving at an appropriate research approach to be adopted. The second part this chapter will illustrate the research design based on the research approach chosen.

4.2 The Methodological Fit

This section explores the *fit* from the following key elements suggested by Ahlstrom (2016) as shown in *Figure 4.2*. The first element concerns the existing knowledge and the knowledge intended to be acquired through this research: *Maturity of Knowledge and Research Questions*. This concerns the generation and capturing of the intended knowledge. Secondly, it is crucial to understand the contribution of this research, or in other words, the intended impact of this research: *Contribution*. Finally, based on the discussion and understanding on the previous elements, it is necessary to evaluate the most appropriate research approach to achieve the above: *Research Approach*.

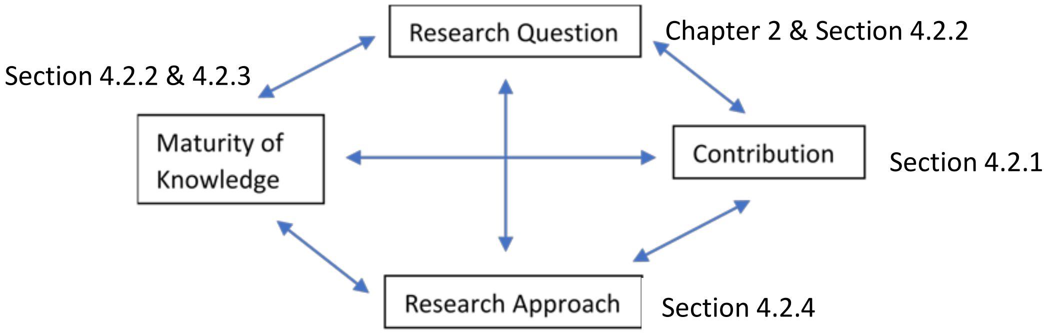


Figure 4.2: Methodological fit between key elements within research project
Source: Adapted from Ahlström, 2016

4.2.1 Professional Doctorate Studies

The contribution of this research can be discussed from the perspective of professional doctorate studies. The efforts from academicians to narrow the gap between theory and practice can be seen with the offering of 'professional doctorates' such as Doctoral in Business Administration (DBA). It is a doctoral course designed for practising managers and professionals. As described in the DBA module handbook (DBA, 2015:3), the design of DBA course focuses on the '*interactive transfer of knowledge and learning between academic theory and professional practice*'. This is in-line with the DBA guidelines by the Association of Business Schools (see DBA, 2015:9) which says:

> '*the DBA has a dual purpose – to make a contribution to both theory and practice in relation to business and management, and to develop professional practice through making a contribution to professional*

> *knowledge. The DBA therefore seeks not only to make a contribution to knowledge but also to inform and impact upon practice.'*

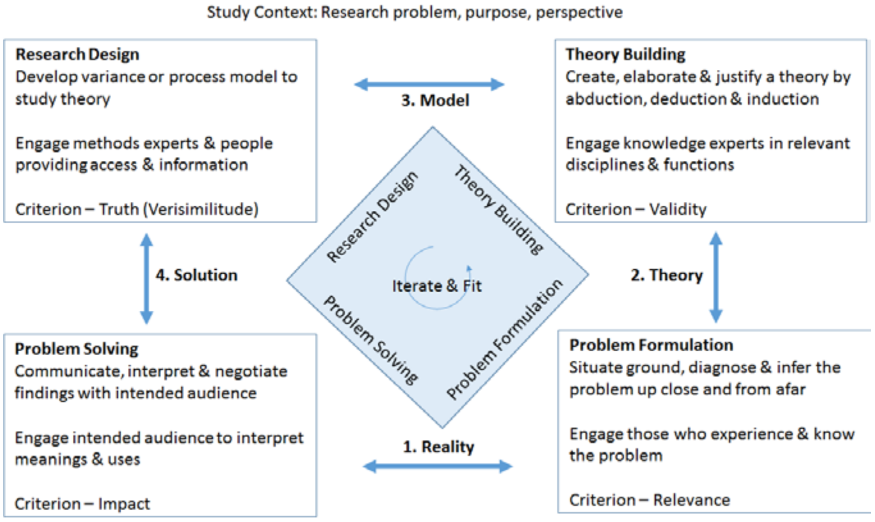


Figure 4.3: DBA Approach Illustrated Using Diamond Model
Source: Van de Ven (2007)

DBA adopts the concept of *Engaged Scholarship* as illustrated in the *Diamond Model* presented by Van de Ven (2007) as shown in *Figure 4.3*. In contrast to traditional PhD which begins its research process from *Theory* phase, DBA begins from the *Reality* phase, where *Problems* in real world are being formulated (DBA, 2015; Van de Ven, 2007). Thus, DBA researchers are normally expected to conduct research on own job, organisation, or industrial sector where the research outcome will be of impact on the one hand to solve the problem by contributing to professional practice, and on the other hand contributing towards the theoretical knowledge of field being researched (DBA, 2015, Perry and Zuber-Skerritt, 1994). This thesis is written to fulfil the requirement of a DBA award. It is the aim of this research to have impact on both the industry and academia.

4.2.2 Research Mode

The fundamental objective of research is the creation and development of knowledge with high quality in its validity and reliability (Karlsson, 2016). Thus, it is crucial to understand the mode of knowledge production. Gibbons et al. (1994) categorised mode of knowledge production into two research modes: Mode 1 and Mode 2.

Knowledge production under Mode 1 is used to refer to the traditional pure knowledge creation and development where theoretical knowledge usually precedes application, as well as a distance is usually maintained in between those applying the knowledge and those producing knowledge (Thorpe et al., 2015:9). The aim is to arrive at a universal or generalizable knowledge within a discipline where findings are validated against with emphasis in prediction and control (Anderson et al., 2001; Coughlan and Coghlan, 2016: 235; Nowotny, 2000).

Mode 2, the antithesis of Mode 1 holds the perspective that knowledge is produced and developed as a result of interaction transpired between theory and practice (Thorpe et al., 2015:9). In addition, it is described as 'context-driven', 'problem-focused' and 'interdisciplinary' (Gray et al., 2011; Karlsson, 2016). This process of knowledge production is increasingly reflexive and is argued to be counted as 'good science' by Gibbons et al. (1994: vii).

The distinction between key features of Mode 1 and Mode 2 are highlighted by Gibbons et al. (1994). The first distinction lies in the motivation of research. Mode 1 problems are pre-defined and solved in a context controlled mainly by academic or interests of a specific community. In contrast, Mode 2 is driven by the context of application. The distinction in motivation affects the boundary of research. Mode 1 is inclined towards disciplinary specific while Mode 2 is transdisciplinary. Driven by the motivation to provide a solution to a practical problem, Mode 2 explicitly acknowledges the dynamicity and unpredictable in practical world. Thus, an evolving framework is generated and sustained in the process of problem solving. The purpose is to capture and accumulate knowledge without being restricted by any discipline.

The difference in disciplinary boundary affects diversity of participants. Mode 1 is characterised by homogeneity, whereas Mode 2 by heterogeneity. This is particularly evident in the skills and experience brought into the problem-solving process. Organisationally, Mode 1 is hierarchical which tends to be restricted to universities and colleges, often preserving its form. On the contrary, Mode 2 is more heterarchical and transient. It is open for collaboration by various institutions or entities. This also means flexibility in its organisation according to the necessity in the problem-solving process.

In comparison with Mode 1, Mode 2 is socially accountable and reflexive where emphasis is placed on the impact, or wider implications of the actions taken. In other words, Mode 2 considers values and preferences of individuals or groups, multiple stakeholders rather than restricting to mere scientific and technical terms. It is thus a collaboration work on a problem detailed in a specific and localised context. Finally, on the quality controls of knowledge produced, Mode 1 is judged from the perspective of discipline via peer evaluation process.

Mode 2, due to its wider involvement and implications will then require evaluation from a wider perspective to include the concerns of community of interest. The objective of highlighting the distinction between the two modes of knowledge generation through research is to create awareness and appreciation towards different ways knowledge can be generated (Gibbons et al., 1994).

Other than the above two research modes, Huff and Huff (2001) argues that there is the third research mode, Mode 3, which is directed to help humanity. Although Mode 2 has a wider impact compared to the traditional Mode 1, the beneficiaries are mainly confined to certain entities, for example: firms, government, or commercial/regulatory bodies. Huff and Huff (2001) propose the necessity to enlarge the impact of research where the beneficiary of the knowledge generated is the society.

The research presented in this document is based on a ‘real life’ problem in an organisation. A production planning and control (PPC) system is to be developed and implemented to solve practical problems in workplace. Other than providing a practical solution to the organisation, this project also aims to bridge the gap between the theory and practice in the development and implementation of PPC system. It is transdisciplinary where research participants with different skills and experiences of relevant disciplinary are brought together as the research progresses. A detailed analysis on this research based on the various descriptors highlighted by Huff and Huff (2001) is shown in *Table 4.1*. This table summarises the differences of the three research modes together with an additional column to analyse and justify this research as Mode 2.

Table 4.1: Comparison between Research Mode 1, 2, 3, and the Relevance to this Research
Source: Adapted from Huff and Huff (2001)

Descriptors	Mode 1	Mode 2	Mode 3	**This Research**
Activity Triggers	Theoretical or Empirical Gaps	Practical Problem	Appreciation and Critique	Practical problem faced by company
Participants	Homogenous Sub-disciplines	Activity-centred Transdisciplinary (including Mode 1)	Diverse Stakeholders (including Mode 1 and 2)	Activity-centred transdisciplinary according to necessity/ problem faced throughout the process
Goals	Truth, Theoretical Extension	Solution, Improvement	Future Good	To provide solution and improvement to the problem faced by company
Methods	Pre-tested, Paradigm-based	Often Invented, Based on Experience	Collective Experience, Conversation	Designed based on experience and contextual condition
Activity Site	Sheltered, Laboratory, 'Ivory Tower'	Practice, The Workplace	Society, The Community	The researcher is also an employee of the organisation under-researched, thus, workplace
Time Horizon	Individually Driven, Often Unimportant	Often Immediate or Urgent	Immediate to Very Long Term	Immediate according to the agreed delivery time
Boundaries	Disciplinary, Pure/Applied, Institutional	Transdisciplinary, Often Proprietary	Multiple Modes of Knowing	Transdisciplinary according to skills and experience necessary to provide solution
Beneficiaries	Individual Scientists, Professional Groups	Firms, Government, Commercial/Regulatory Bodies, etc	Society	Firm, Government, University and Researcher
Quality Control	Elite-Dominated, Peer Review	Utility, Efficiency	Community Agreement	Utility, Efficiency, Peer Review
Funding (Primary Source)	University, Government, EU	Business	Philanthropy, University, Business, Government	University, Government, Firm
Dissemination	Scholarly Conference, Academic Journals	Practitioner Conferences, Policy Documents, Internet	Local to Global Debates and Action, Media Reports	Scholarly Conference, Academic Journals, Practitioner Conferences

4.2.3 Theory vs Practice in Operations Management (OM)

The gap between theory and practice has been long observed and criticised. In as early as 1970s, Revans (1971) criticised management education for moving further away from the realities of business world, introducing irrelevant academic information and creating a virtual wall between theory and practice. Susman and Evered (1978) described this widening gap as a *crisis*, questioning the sophisticated research methods and techniques adopted in academic which are irrelevant to solving practical problems in the real world. In late 1980s, reports and findings by Behrman and Levin (1984) and Porter and McKibbin (1988: 170) shows that senior executives are doubtful about the direct impact academic research has on management and organisational practise. In the late 1990s, Cohen et al. (1998) reported that the situation has gradually improved. The emergence of new economic opportunities due to globalisation, the help of favourable public policies for academic-industry collaborations, and the shift of resource dependencies from public to private, have resulted positive response from both academicians and practitioners to increase collaborations in creating new knowledge (Rynes et al, 2001).

In the field of operations management (OM), the gap between theory and practice is well observed. As described by Karlsson (2016:12), OM field is an '*applied field with a managerial character*'. It deals with 'real world' problems and challenges and is '*cross-disciplined*'. The applied nature of OM has prompted researchers, such as Flynn et al. (1990) and Westbrook (1995) to stress the need to adopt empirical and field-based methodology in OM research. Westbrook (1995) highlighted the lack of applicability in the research conducted by OM academics, which results in the lack of academia influence over practitioners. He strongly criticised the 'reductionist' approach in understanding OM by breaking it into different parts in isolation rather than adopting an 'integrative' approach, which investigate the impact of OM in a systemic view.

In the context of the design and implementation of an effective production planning and control system, researchers have red-flagged the various attempts to over-simplify firms into structured mathematical problem definitions (Arica et al., 2016; Berglund and Karltun, 2007; Karltun and Berglund, 2010; Jackson et al., 2004). Instead, acknowledging the heterogeneity nature of organisation in the 'real world', these researchers have called for the design of contextual knowledge based PPC, and to integrate human, the 'embodiment' of tacit knowledge, into the implementation of PPC. The concept of 'tacit knowledge' has been crystalized by Polanyi (1966:4) into one phrase: '*we can know more than we can tell*'.

As described by Nonaka et al. (2000), there are two types of knowledge: explicit and tacit. Explicit knowledge can be codified, processed, shared and stored. With the advancement in information technology, accessibility of explicit knowledge has been greatly increased. On the contrary, tacit knowledge is personal in nature and difficult to be formalised. It is normally found, for example, in values, commitment, action, procedures and emotion (Seidler-de Alwis and Hartmann, 2008) which could only be acquired by sharing experiences, observation, and imitation (Kikoski and Kikoski, 2004). As described by Brocklesby (2016), what happens in real-life, is an evolving 'present'. Tacit knowledge is simultaneously generated through interactions among people, reflections on experiences, and the negotiations and actions taken in decision making processes.

It is the aim of this research to bridge the gap between S-DBR theory and practice, particularly concerning the issues experienced in S-DBR implementation process (research question 2). Other than understanding the assumptions used in S-DBR concept (theory), it is also the aim of the research to understand how S-DBR fits into contextual environment (practice), which includes capturing relevant *tacit knowledge*. As this research project involves intervention where an S-DBR based PPC system is to be developed and implemented, the next section will further explore the appropriate research approach which is aligned to knowledge generating and capturing, as well as contributes towards both practice and academia.

4.2.4 Research Approach

As discussed in Section 4.2.1, the researcher is enrolled in pursuing a professional doctorate degree: DBA. As a business system architecture designer/programmer in the company, the researcher has chosen to undertake the research at own workplace, seeking to contribute to workplace practice according to the work context. It is also the aim to capture *work-based* knowledge generated in this process as a contribution towards the body of knowledge of operations management. *Work-based* knowledge is generated through learning from real-life experience (Costley and Lester, 2012;

Doncaster and Lester, 2002; Raelin, 2015; Shani et al., 2012). The underlying epistemology is the recognition that knowledge is not permanent nor resides outside of human experience. Rather, it is fluid and contextualised, created via the interactions the researcher has with other research participants. In this interaction, each individual contributes own interpretations and suggestions to address a practical problem (Shani et al., 2012; Raelin, 2015). As illustrated by Coghlan (2010), the meaning of the world we lived in is constructed based on our empirical experiences, understanding, and judgement. Thus, it is crucial for the researcher to interpret and make sense of own and other's interpretation.

It is inadequate to merely reside in understanding or explanation. It is crucial to take action according to the judgement made. Similarly, due to the acknowledgement that there are no two situations which are identical at a given time, this knowledge needs to be constantly 'renewed' or 'updated' by inquiring into the construction of meaning made by individual or group in their interaction with the surrounding world for the task at hand (Shani et al., 2012).

Kurt Lewin (1946), the founder of Action Research (AR) highlighted two critical assumptions in generating knowledge through taking action. The first assumption holds the view that through reflection, the engagement of fellow research participants produces better learning. In addition, it produces more valid data regarding the way a system works. Involvement of members of the human system in the inquiry process is critical as it facilitates the development of understanding in the human system (Coghlan and Shani, 2014). According to its second assumption, a system can only be understood if one tries to change it by taking action (Coughlan and Coghlan, 2016). Through intervention (taking action), knowledge will be generated (Argyris, 2005).

The result of generating knowledge through action is the change in status quo and in creating *liberating alternatives*. As every *problem* encountered is contextual, the knowledge generated through action is always contextualised and is not able to be predicted by universal propositions (David and Hatchuel, 2008). The research approach of adopting AR in own work place is known as insider action research (Coghlan, 2007). The interventionist nature of this research approach aims to observe, analyse and bring changes to the organisation.

In the context of management and organisation studies, Shani and Pasmore (2010) define AR as:

> ‘*an emergent inquiry process in which applied behavioural science knowledge is integrated with existing organisational knowledge and applied to solve real organisational problems. It is simultaneously concerned with bringing about change in organisations, in developing self-help competencies in organisational members and in adding to scientific knowledge. Finally, it is an evolving process that is undertaken in a spirit of collaboration and co-inquiry’.*

From the definition above, the first critical theme highlighted is ‘*emergent inquiry process*’. Rather than treating knowledge as *exhaustive* or *stagnant,* AR engages research in present tense, which Shani et al. (2012) illustrated it as ‘*build on the past, take place in the present with a view to shaping the future*’. This process requires attentiveness and reflexivity on the things which happens in any instance with the purpose to issue in certain purposeful action. It is also described as a process which engages in unfolding story as consequence of intervention through action is not predictable or controllable.

The second critical theme is that it involves *real organisational problems* rather than it is created for the purpose of research. As it is *real,* it involves people-in-system as well as the *behavioural science knowledge*. This leads to another critical theme which is the dual objectives of AR: to contribute both as a scholar to the academia and as a practitioner to the industry. The final critical theme illustrates the way the AR research is carried out. It features a research constructed *with* people, rather than *on* or *for* people (Shani et al. 2012).

AR has been highlighted by MacLean et al. (2002) as one of the research methodologies adopted in management research which is in-line with Mode 2 research criteria. This is further supported by Levin and Greenwood (2008) who advocate AR as the way forward for higher education to generate actionable knowledge through constructive problem solving which is beneficial to various stakeholders including non-university stakeholders. Actionable knowledge refers to knowledge which are useful to both the academic and practitioners (Adler and Shani, 2001). In advocating using AR to generate robust actionable knowledge in management and organisation studies, Coghlan (2007; 2011) stresses the similar features shown by both AR and Mode 2 in transdisciplinary collaboration, reflexivity, as well as similar objective in co-generating actionable knowledge. As illustrated by Costley and Lester (2013), AR is able to capture practical knowledge as described in Mode 2, a research approach which best fit professional or work-based doctorate.

In view of the above discussions, AR is seen as offering the ‘fit’ and aligns with the research questions, knowledge to be generated and captured, and the dual purpose contribution of this professional doctorate. The following section will discuss and highlight the characteristics of AR in relation to this research, which will form as a guide to the design of this research.

4.2.5 Characteristics of Action Research

Based on the ten major characteristics of AR laid out by Gummesson (2000), Coughlan and Coghlan (2016) re-describe them in the context of OM. Below are the summary of the characteristics highlighted, together with the discussion on how it *fits* with the research presented in this thesis. These characteristics are embedded in the AR Cycle Design as illustrated in section 4.3.

1) *Action researchers take action*. AR emphasises research *in* action, rather than *about* action (Coughlan and Coghlan, 2002). In addition to observation, actions are taken to make it happen. The researcher, working as employee of the organisation is not merely tasked to observe and identify areas and methods to improve, it is required to take action to introduce and implement the best practice intervention in the organisation. The action is taken consciously and deliberately through multiple cyclical processes with four steps: planning, taking action, evaluation of the action, which leads to further planning.
2) *Action research always involves two goals*: problem solving and contribution to science. This research shares the similar dual objectives of professional doctorate and KTP. On the one hand, to provide solution to the practical problem in the company; and on the other hand, contributes towards the body of knowledge of OM.
3) *Action research is interactive*. Researcher collaborates with a team of experts from firm and university to co-work and resolve issues which arises from the unfolding and unpredictable events. The setting of the KTP collaboration

involves a core team consisting of experts from various departments within Amberol, Nottingham Business School and Nottingham School of Science and Technology to co-design a best practise intervention which is suitable for Amberol context. This setting will be further leveraged to carry out this research.

4) *Action research aims at developing holistic understanding during a project and recognising complexity*. In this research, as a practitioner working in own organisation, the action researcher is able to have a systemic view and the ability to work across both the formal and informal organisation structure acknowledging the dynamic complexity which may arise in real life.
5) *Action research is fundamentally about change*. In OM, AR is applicable as it concerns the entire change process. This includes the recognition of the organisation on the need to change, to set out a desired outcome from the change, as well as to actively plan and execute to achieve the intended outcome (Coghlan and Brannick, 2014). In this research, with KTP as the backdrop, it is the objective of the company to introduce change in its manufacturing process.
6) *Action research requires an understanding of the ethical framework, values and norms within which it is used in a particular context.* In OM, other than systems and process, *people* are also the focus. As the outcome of AR has impact either directly or indirectly on *people* within firm, it is necessary to ensure actions taken are underpinned by ethical considerations. The explicit acknowledgement of AR on *people* fits well with this research as it is part of research question 2 to identify how *people* plays a role in the implementation of PPC system (As detailed in Section 3.6.1).
7) *Action research can include all types of data gathering methods*. The data gathering method can be either qualitative, quantitative tools or both. The emphasis is the most suitable method according to suitability agreed in advance with the members of organisation. It is highlighted by Coughlan and Coghlan (2016) where the data-gathering methods themselves are interventions and generates data. For example, with the usage of interview, it may generate various feelings such as anxiety. This is particularly important as in OM, on the one hand, it might need to process *hard data* to make decisions on areas such as process technology; on the other hand, it also

generates *soft data* such as employee motivation, which also brings impact on output performance. In this research, working on own company, the researcher deals directly with observable phenomena in an organisation. This includes the observation of practices which are embedded in the daily routine of a business yet not explicitly documented. As highlighted by Coughlan and Coghlan (2002), this observation is a critical source of data where further inquiries can be constructed.

8) *Action research requires a breadth of pre-understanding* of the dynamics and structure of operating systems and the underpinning theoretical of such system. In addition, it is also necessary to pre-understand the corporate culture and business environment in which the operating systems is interacting with. This has been highlighted by Skinner (2007) who emphasises the need of a fit, an alignment and coherence of manufacturing operations with business strategy (Coughlan and Coghlan, 2016; Gonzalez-Benito and Lannelongue, 2014).
9) *Action research should be conducted in real time, although retrospective action research is also acceptable*. As AR is an emergent inquiry process, it is described as a 'live' case study by Coughlan and Coghlan (2016). However, they also recognise the use of *retrospective* of previous *cases* as an intervention into the present organisation.
10) *The action research paradigm requires its own quality criteria*. As AR belongs to Mode 2 research, it is not appropriate to be evaluated using Mode 1 research criteria. In conducting AR, Reason (2006a) highlighted that it is a process full of choices. Thus, it is necessary to be conscious about the choices available as well as the consequences of these choices. It is argued that the quality of AR is based on the transparency of these choices, consequences, and decision of choice. It is opined that actionable knowledge is produced through rigorous and critical evaluation of these choices. In 2008, Pasmore et al. suggested the use of three broad criteria to determine the quality of AR: *rigorous*, *reflection* and *relevant*. *Rigorous* includes data-driven, multiple methods, reliability across settings, co-evaluation, causality, underlying mechanism and publishability. Under *reflection*, they have grouped historical impact, referential, co-interpretation, community of practice, collection and repeated application. As for *relevant*, it includes practical, codetermined, re-applicable, teachable, face-valid, interesting, true significance and specific. These criteria

has been further framed into seven key areas by Coghlan and Shani (2014): purpose and rationale for action and inquiry, context, methodology and method of inquiry, design, narrative and outcomes, reflection on the narrative in the light of the experience and the theory. With regards to the quality in AR, Coughlan and Coghlan (2016) summarise as below:

‘*action researchers need to show how they engaged in cycles of action and reflection in collaboration with others, how they accessed multiple data sources to provide contradictory and confirming interpretations, what choices were made along the way and how they were made, provide evidence of how they challenged and tested their assumptions and interpretations continuously throughout the project and how their interpretations and outcomes were challenged, supported or disconfirmed from existing literature*’.

4.2.6 Action Research Cycle

The implementation of AR involves two parallel AR projects (Coghlan and Brannick, 2014; Coughlan and Coghlan, 2016; Perry and Zuber-Skerritt, 1994). The first is called the core AR project, and the second is the thesis AR project. The core AR project, as illustrated by Perry and Zuber-Skerritt (1994) involves the AR researcher as part of the workgroup of practitioners from the organisation, the world of practice. This is linked to the thesis AR project where a ‘workgroup’ consisting of the AR researcher, fellow AR researchers and their supervisors, with the aim of fulfilling thesis requirement. Coughlan and Coghlan (2016) regard this group as people

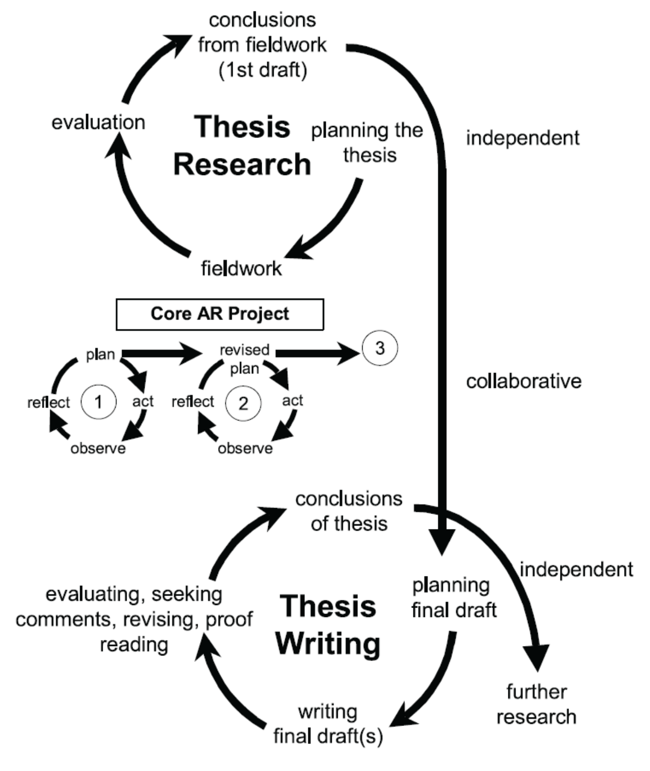


Figure 4.4: The Parallel AR Projects
Source: Perry and Zuber-Skerritt (1994)

who are familiar with the key concepts, knowledge of literature as well as operations practice. This is to provide a research-based inquiry into the core AR through similar cycles of action and reflection matching the core AR as it develops iteratively.

The existence of two parallel cycles allows the flexibility of having different area of research interest. Zuber-Skerritt and Perry (2002) illustrate by giving the example where core AR project's main concern is the strategic planning of the organisation, whereas for thesis AR project's concern could be from the perspective of cultural change. It is from these cycles of action and reflection where co-researchers collaboratively generate actionable knowledge. As illustrated by Lewin (1946: 146), it is '*a continuous spiral of steps, each of which is composed of a circle of planning, action and fact-finding about the result of the action*'.

Based on this, Coghlan and Brannick (2014) presented an AR cycle which comprise of a '*pre-step*' and four main steps: '*constructing*', '*planning action*', '*taking action*', and '*evaluating action*'. Within these cycles lies the core of AR projects, which Coughlan and Coghlan (2016) address it as '*Meta-Learning*', which means learning about learning. Through inquiries and reflections on the steps of these learning process cycles, actionable knowledge is generated (Argyris, 2003).

According to Mezirow (1991), there are three forms of reflections: content, process, and premise. *Content* is related to the issues, *Process* is related to the strategies and procedures, and *Premise* is related to the underpinning assumptions and perspectives. Based on these three forms of reflection, Coghlan and Brannick (2014) highlighted the criticality of all three forms of reflective and relate them to the AR cycle to form 'meta-inquiry' (Coghlan and Brannick, 2014; Coughlan and Coghlan, 2016).

In relating to '*Content*', continual inquiry into the construction of the four main steps of AR is required. This includes the way the steps are carried out, their consistency with each other, as well as consistency with the objective. '*Process*' reflection is necessary to evaluate how the constructing is undertaken, how actions are implemented, how evaluation is conducted, and how it leads to the subsequent cycles. The '*Premise*' reflection is meant to inquire into the unseen, informal, unstated, and taken for granted assumptions which results in certain behaviour or attitude.

The advantage of action research in generating contextual knowledge is a double-edged sword where its repeatability and generalisation being questioned (Eden and Huxham, 1996). As highlighted by Coughlan and Coghlan (2016), theory is fundamental to OM research. The practicality nature of OM requires the research to contribute to OM theories from domain-specific perspectives. The explicit aim of contribution to theory distinguishes AR with other seemingly similar cyclical diagnosis approach into problem solving, such as experiential learning, quality improvement, project management, prototyping, and consultancies (Coughlan and Coghlan, 2016: 240; Gummesson, 2000; Whitehead, 2005;).

As action knowledge is generated in AR through interplaying knowledge and action, Coughlan and Coghlan (2016) highlight the three characteristics of theories generated by AR as *situation specific, emergent*, and *incremental*. The first characteristic shows that the contextual nature of AR does not carry the intention to create universal knowledge. With this intention, the research purpose emerges is a synthesis of both the reflection on data gathered from the core AR cycle and the application of OM theory in practice unfold through the cycles.

In the design of the AR design, it is thus not possible to design all cycles in advance. Based on the stated aim of the project, only the first cycle is able to be designed. The design of subsequent cycles are dependent on reflections from the previous AR cycle. The first AR cycle will be discussed in detail in the following section.

4.3 Research Design

As discussed in Section 4.2, the emergent and incremental characteristic of AR means it is not possible to design all AR cycles in advance except for the first AR cycle. With reference to *Figure 4.5*, the *Context* and *Purpose* part of the AR cycle has been discussed in Section 3.2. This includes the purpose of this research as well as providing justification for research methodology to be adopted and philosophical position of the researcher. This section will begin by introducing Knowledge Transfer Partnership (KTP) and its relevance to this research. This is followed by an illustration on the design of the first AR cycle together with its four main-steps: *Constructing*, *Planning Action*, *Taking Action*, and *Evaluating Action*, as shown in *Figure 4.5*.

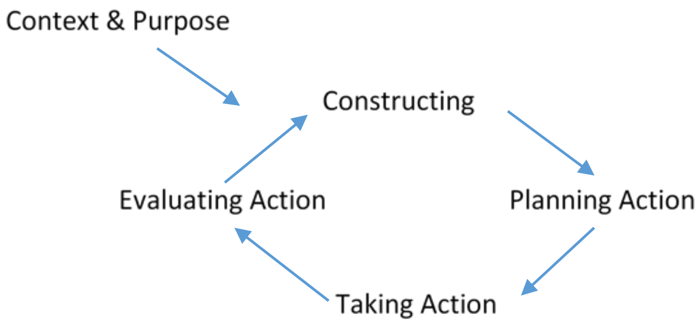


Figure 4.5: The Action Research Cycle

Source: Coghlan and Brannick (2014: 9)

4.3.1 Knowledge Transfer Partnership (KTP)

KTP is a scheme set up by the UK government to help businesses in the UK to innovate and grow. There are four collaborative partners in this scheme:

(i) Innovate UK, a UK government agency who funds the major portion of this project, with the objective to ‘*enable a business to bring in new skills and the latest academic thinking to deliver a specific, strategic innovation project through a knowledge-based partnership*’.

(ii) Business entity, a host company: Amberol Ltd, will be known as Amberol in this document, who partly funds this project. Other than being the host company, Amberol is also the company under research in this professional doctorate study.

(iii) KTP associate. In this KTP project, the associate, who is hired to work in Amberol as a business system architecture designer/programmer, is also the researcher in this professional doctorate study.

(iv) Research Organisation, which in this case is Nottingham Trent University. Due to the complexity of the project, it involves both Nottingham Business School and School of Science and Technology. This offers a trans-discipline collaboration and both *hard* (computing and software development) and *soft* (management philosophies) knowledge and skills.

As an intervention project, three main phases are introduced as an overarching structure of the project: *Pre-change*, *In-change* and *Post-change*. These phases are adopted to guide AR core project. The relationship between the research questions formulated to guide the AR thesis project, the project phases, main stages of KTP project and duration are shown in *Table 4.2*. The use of KTP project management and monitoring structure and mechanism offers a formal and independent platform to validate the various data collected, findings, actions, output, and impact of this research. In addition, documentation and correspondence within this mechanism is used as a source of data for this research. With the overall understanding of KTP project as the backdrop, the next section will continue to discuss and demonstrate the AR cycle design.

Table 4.2: Overview of Macro AR Cycle in relation to Research Phases

Phases	Pre-Change	In-Change	Post-Change
Main Stages within KTP	**Stage 1**: Internal audit and need analysis	**Stage 2**: Develop and test discrete system elements. **Stage 3**: Develop and implement system	**Stage 4**: Consolidate and embed system.
Research Questions (RQ)	*RQ1: What are the concepts underpinning S-DBR and how can they be configured to meet specific MTO contextual environments?*		
		RQ2: *What are the implementation issues in S-DBR and how may they be addressed?*	
Over-arching macro AR Cycle	Context & Purpose, Constructing, Planning Action	Taking Action	Evaluating Action
Time Scale	3 months	15 months	6 months

4.3.2 Macro Action Research Cycle Design

With reference to *Table 4.2*, this section will illustrate the details of the macro AR cycle designed as an over-arching cycle of this research.

STEP 1: Constructing

The objective of this project has been described in section 4.3.1, where an appropriate production planning and control system is to be developed and implemented in Amberol. An internal audit and need analysis is necessary to inform the subsequent steps. In order to develop a holistic view, collaborative effort is necessary (Coughlan and Coghlan, 2016; Coghlan and Brannick, 2014).

To facilitate *collaboration*, five core research groups will be formed. One of the groups is formal whereas the rest are informal. The formal research group leverages on the KTP setup with each consists of various stakeholders of this project. This offers different communication platforms and perspectives.

The first group is made up of the official KTP project committee. The various stakeholders in this group are from Amberol: Managing Director, Executive Director, and the researcher; from Nottingham Trent University (NTU): Reader in Operations Management from Nottingham Business School (NBS), and Senior Lecturer in Computing and Technology from School of Science and Technology (SST); and lastly, a representative from Innovate UK. Being the main sponsors and stakeholders of the project at its highest level, the team meets quarterly to monitor the overall progress and direction of the project.

The second group consists of the Managing Director, researcher, as well as Reader and Senior Lecturer from NTU. This group is meant to meet more regularly to discuss, evaluate and make necessary decision about the research progress, providing the theoretical conceptual underpinnings to the proposed solution.

The third group is more dynamic, consisting of the Managing Director, Sales Manager, Production Manager, Admin Manager and researcher. This group meets as and when it is necessary. The members could also vary accordingly depending on knowledge and skills required. *Figure 4.6* illustrates the core groups with the associated members.

The fourth group consists of only the production manager and the researcher. This is where various day-to-day manufacturing related inquiries and discussions occurs.

The last group, which is crucial to the success of the project, is only between the Managing Director and researcher. This group is crucial as it allows direct communication between the top management and researcher.

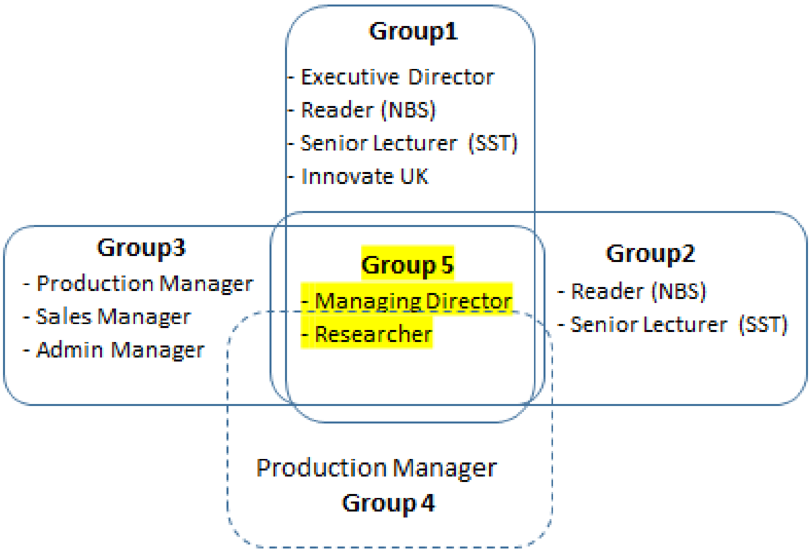


Figure 4.6: The Five Core Research Groups

The purpose of having these groups, and particularly involving the Managing Director in three groups is seen as crucial in implementing this project. From the perspective of core AR project, it shows the determination of the organisation in executing the project. The involvement of multiple stakeholders from every level within the organisation is to ensure the project is aligned with the strategic direction of the organisation. The involvement of senior management from various departments is to facilitate quick approvals on necessary actions in the AR cycles. Lastly, as the Managing Director is also the owner of the company, it provides continuity in the development of organisational self-help competencies if the organisation involves in other future AR cycles (Shani and Pasmore, 2010). This is also referred as *sustainable change* by Coghlan and Branninck (2014).

From the perspective of thesis AR project, these groups, consist of different levels: *individual*, *team*, *inter-department group*, and *organisation*, provide inter-level analysis which could enrich and validate the authenticity of data collected. This is critical as it informs the next course of action to be taken (Coghlan and Brannick, 2014:102).

STEP 2: Planning Action

Upon constructing the issues underpinned by the overall context and purpose of the project, Coughlan and Coghlan (2016) suggest some key questions to assist action planning in both the core and thesis AR project. *Table 4.3* and *4.4* shows the response to these questions for both projects.

Table 4.3: Core AR project

Key Questions	Response
What needs to change? In what parts of the organisation? What type of change are required?	As identified by the KTP proposal, change is targeted on the manufacturing department in its manufacturing process. This is proposed to be done through the development and implementation of a TOC based production planning and control system. As the system is anticipated to be an integral part of the organisation as a whole, it is necessary for the developed system to integrate with the existing ERP (Enterprise Resource Planning) system used in Amberol.
On what timescale?	2 years (2015 – 2017), as planned in the KTP proposal.
Whose support is needed?	It requires the support of all levels within the organisation. The KTP setup and core teams setup as described under *Step 1: Construction* is anticipated to realise this.
How is commitment to be built?	It is a win-win situation for all stakeholders with the KTP framework. • Amberol is in need of a breakthrough in its production process and operating performance. It has also committed itself into both monetary and non-monetary investment into this project. • Innovate UK, shown its commitment into this project with its grant approval anticipates positive impact to all stakeholders of this project, with implication to the wider UK economy. • NTU, shows commitment by offering DBA enrolment opportunity to the researcher, with anticipation of a successful industry collaboration, contributing towards narrowing the gap between theory and practice. • The researcher, with his previous managerial experience in telecommunication industry as solution provider, is interested to venture into developing solution for manufacturing industry.

How is resistance to be manage?	To be managed via the teams/groups set up in *Step 1: Construction*.

Table 4.4: Thesis AR project

Key Questions	Response
What kinds of data? How might the data emerge and be captured? What access will be required to whom, when and on what terms?	Both 'hard' and 'soft' data as described in *Step 1: Construction* and Section 3.4. Details on operation performance measurement related data are described in Section 2.7.
On what timescale?	2 years (2015 – 2017), as planned in the KTP proposal.
What will my involvement be? In what meetings will I participate? What will I do? Whom can I meet within and outside of the firm?	The researcher is also the practitioner, actively taking action to develop and implement the core AR project. The involvement of the researcher is shown and discussed in *Step 1: Construction*.
How will research and data integrity be maintained? How will I maintain trust and confidentiality?	Research and data integrity will be maintained through the formal KTP project management mechanism as well as through the teams/groups set up in *Step 1: Construction*. Other than the KTP structure, trust and confidentiality is maintained through the professional and ethical awareness and practice of the researcher which will be discussed in more detail in Section 3.5 of this Chapter.

STEP 3: Taking Action

This step involves two main stages within the planned core AR project: (i) Develop and test discrete system elements and (ii) develop and implement system. In this step, the main design blocks of the S-DBR based production planning and control system is being developed based on the elements found in generic S&T tree used by Theory of Constraints practitioners. The focus will be on the five elements under element 3.1.1: 'Remarkable Due Date' as shown in *Figure 4.7*: (i) Choking the release, (ii) Managing the priorities, (iii) Dealing with capacity constraint resources, (iv) Load control, and (v) Systemically improving flow. Each of the above elements will be analysed and discussed against actual implementation. *Table 4.5* is an example on the details of element 4.11.1 ‘Choking the Release’.

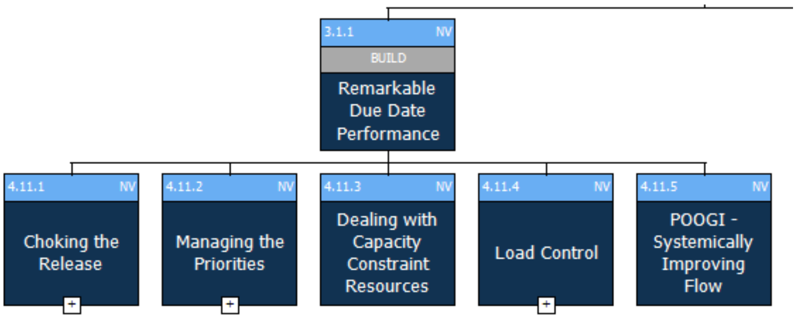


Figure 4.7: Generic S&T Tree to achieve Remarkable Due Date Performance
Source: Harmony (2017)

4.1.1: Choking the Release

Table 4.5: S&T Element 4.11.1: Choking the Release

Need for Change Having too many orders on the shop floor masks priorities, promotes local optima behavior and therefore prolongs the lead-time and significantly disrupts Due-Date-Performance (DDP).
Strategy The shop floor is populated ONLY with orders that have to be filled within a predefined horizon.
Change Assumptions • In traditionally run plants touch time is a very small fraction (<10%) of the lead time • Vast experience shows that, in traditionally run plants, restricting the release of materials, to be just half the current lead time before the corresponding due date, leads only to good results, and to not negative ramifications * (lead time reduces to less than half, DDP improves significantly, Throughput goes up and excess capacity is revealed). These results are achieved irrespective of whether a bottleneck exists or not. **Except for environments which are dominated by heavily dependent set-up matrixes. Those environments have to be dealt with in a different way.*
Tactic • For each group of products currently having similar lead times, a buffer time is set to be equal to 50% of the current that lead-time. • Orders are released to the floor only a buffer time before their committed due-date - excessive Work-in-Process (WIP) is frozen until its time arrives according to the above rule.

Warning: Do not use the shorter lead time as standard practice to get more sales
Warning Trying to be more accurate than the noise is useless, distracting, and definitely delays results.

To realise ‘Choke the Release’, there are four necessary elements to be executed as shown in *Figure 4.8*. These elements are ‘Set production time buffers’, ‘Generate release schedule’, ‘Obey the release schedule’ to avoid ‘Excessive WIP’. The content of 5.111.1 ‘Set production time buffers’ is shown in *Table 4.6* as an example.

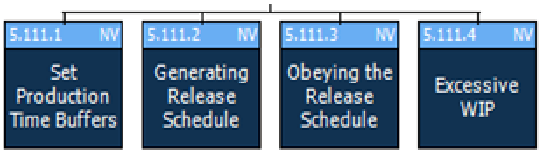


Figure 4.8: Generic S&T Tree on ‘Choking the Release’
Source: Harmony (2017)

(i) 5.111.1: Set Production Time Buffers

Table 4.6: S&T Element 5.111.1: Set Production Time Buffers

Need for Change • Having a production time buffer which is too short or too long, results in chaos and jeopardizes DDP. • If the buffer is too short, there is not enough time and expediting increases. • If the buffer is too long, there is too much WIP, priorities are masked and the lead time is unnecessarily increased. • Applying a unique buffer for each product having a different production lead time may result in too many buffers, bringing about complexity for no reason. • Applying a single buffer for products having considerably different lead times creates chaos.
Strategy The Company has appropriate size production time buffer(s).
Change Assumptions • When setting the buffer, trying to be more accurate than the noise does not help, but rather can cause damage (a fundamental concept of TQM). In the extremes - when the buffer is much too short or much too long - there is chaos. • Between these two extremes there is a large plateau.

• In traditionally run plants, work is released much ahead of the due date (the second extreme) to the extent that there is too much inventory and priorities are masked. • Therefore, in traditionally run plants, cutting the current production lead time by 50% will safely move the system away from one extreme without the danger of reaching the other extreme. (See U-Curve Hyperlink) • When there are processes with significant* static** lead times (such as heat treatment, some outsourced production processes, etc.), this lead time should not be cut into half when determining the buffer. Note: Transportation times should not be considered when determining production time buffers More than one production buffer is set ONLY in cases in which the resulting production buffers are significantly* different. ---- • * Significant means more than one quarter of the buffer. • ** Static processes means operations that cannot be shortened.
Tactic • Production Time buffers are set to be equal to 50% of the existing production lead times. • Significant static lead times are handled properly. • Different production buffers are created ONLY when the difference between production buffers is larger than one quarter.
Warning

STEP 4: Evaluating Action

Evaluation is an important step where outcomes of the core action is reflected on. The ultimate evaluation is to increase the operation performance of the company. As discussed in Section 3.7, this includes both financial and non-financial data. Other than evaluating the final outcome, Coughlan and Coghlan (2016) stressed the importance of evaluating the process itself with the following suggested questions to assist evaluation:

- *Was the original constructing useful, enabling and relevant – looking back was I on the right track?*
- *Was the content of the action taken appropriate?*
- *Was the action taken in a timely, efficient and ethical manner?*
- *What feeds into the next cycle of constructing, planning and action?*

The evaluation of action is also important as it provides input to strategically enable continuous improvement to Amberol.

4.3.3 Data Generation and Collection

As highlighted in Section 4.2.4, AR is an '*emergent inquiry process*' which '*build on the past, take place in the present with a view to shaping the future*'. In this process, *new* data are generated through AR cycles and are used to inform the construction of subsequent AR cycles. In these cycles, *new* data are generated after action, and it is necessary to collect these data.

For data to be effectively generated and collected, the first, second, and third person practice will be adopted (Coghlan and Brannick, 2014:7). First person practice refers to the reflection cycles happening in researcher. Journal or research diary will be kept to note observations, encounters, experiences and reflections. The purpose is to enable data generation by reflecting on both information captured in practice and existing theories. This enables researcher to gather internal feedback, understand conflicting demand between theory and practice, and deal with them.

Due to Amberol being a small company with twenty-five staff, data is collected via formal and informal settings. Formal settings include meetings/interviews/discussions conducted in groups or one-to-one. Observations and engagement with all levels of staff within the organisation will adopt informal settings, which includes over coffee, meals, or other recreational settings. In addition to direct communication with people, job shadowing and observation of actual practice is also essential (Bendoly et al., 2010; Crawford, 2001; McKay, 2001).

The data collected can be both *hard* and *soft* data. *Hard* data includes financial, sales, manufacturing related data and other relevant and obtainable data from the organisation itself. *Soft* data refers to the subjective nature of these data, which includes suggestions from organisation personnel in various department and levels.

With the purpose to understand the contextual environment including the customs and habits of people, McKay (2001) highlighted the need to be '*seen as one of them*'. He highlights the importance '*to sit, observe, and work with the dispatchers and schedulers on a daily* base' to gain an '*intimate knowledge of the plant, products and processes*'. The purpose is to emphasise on *collaboration* in feedback gathering and open discussion (Coughlan and Coghlan, 2016). Forms of data recording includes minutes of meetings, field notes, diary, interview notes and direct observation (Jackson et al., 2004)

Second person practice will make use of Group 2, 3, 4 and 5 designed in section 4.3.2. Each of this group consists of different project stakeholders. Data generated and collected under first person will be reflected on together with relevant group. Group 2, which is consists of researcher and knowledge partners from the university will provide further insight from theoretical perspective. Group 4, which is of researcher and production manager can provide input from shop floor or manufacturing perspective. For issues which requires a wider or systemic perspective, Group 3, which is consists of stakeholders from non-manufacturing, or Group 5, which is consists of researcher and managing director, will be engaged. The data generated from these discussions will be collected in journal or research diary of the researcher.

In this research, data generation and collection through third person practice will make use of the formal setting of Group 1. With the inclusion of project stakeholders external to the organisation and director levels within organisation, it has a formal setting where quarterly meetings are convened to review the progress and direction of the project. Data generated and collected in both first- and second-person practice will be presented to Group 1 audience, known as the Local Monitoring Committee (LMC). Data generated will be collected in the form of minutes of meetings and research diary of researcher. The planned data generation and collection points are illustrated in *Figure 4.9*.

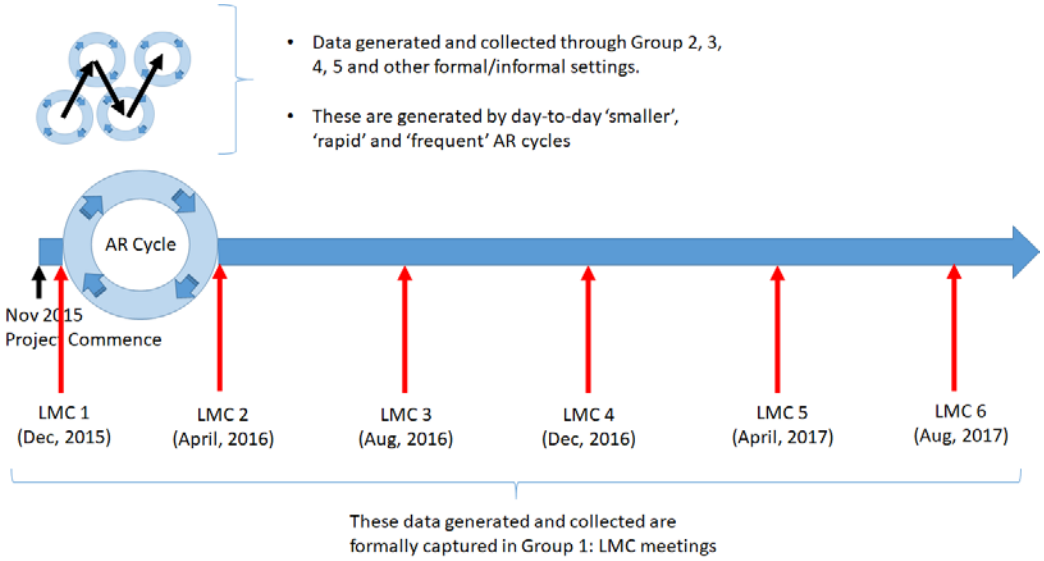


Figure 4.9: Planned Data Generation and Collection Points

To facilitate systematic data collection, recording, analysis, knowledge capturing and dissemination, the following tools and frameworks are proposed to be used in this research These are illustrated in the conceptual framework developed in section 3.8:

(i) S&T Tree

As discussed in section 3.3.6 and section 4.3.2, the generic S&T tree for S-DBR will be used to guide S-DBR implementation. It will also be used to capture any assumptions challenged, amended or any new elements added. As S&T elements capture the *reasoning* and *assumptions* behind action taken, it is anticipated that the data captured will facilitate continuous improvement within Amberol as well as to facilitate knowledge dissemination.

(ii) PPC Implementation Issues

Framework discussed in section 3.6 will be used as the foundation to capture implementation issues encountered.

(iii) PPC Design and Development

Framework discussed and developed in section 3.6.1, which combines both human role and decision support system design, will be used to inform, capture and analyse issues related to PPC design and development.

(iv) Operating Performance Measurement

Operating performance related data to be captured will be informed by section 3.7. It covers both quantitative and qualitative data.

4.4 Ethical Consideration

To undertake the AR cycle successfully, Coughlan and Coghlan (2002) highlighted the importance of developing authentic relationship between researcher and the organisation. In conducting AR, two values have been highlighted by Shani and Pasmore (2010): '*trust*' and '*demonstrated concern for others*'. These values are crucial in determining the level of openness as well as risks involved in the AR process. Coughlan and Coghlan (2016) described it as an understanding of the ethical framework of the organisation.

While it is crucial to value ethics from a personal perspective to perform research authentically, Coghlan and Brannick (2014: 145) also advocate the importance to consider ethical value from the second- and third-person perspectives. The second person perspective involves collaborating with others to arrive at a common ethical value to carry out the project. The third person perspective involves articulating actionable knowledge out of the ethical action taken.

In conducting this research, the researcher will adhere to the Statement of Ethical Practice published by BSA (British Sociological Association) in the aspects such as treatment of research participants, relationship with sponsors, researchers, and group members, as well as upholding research integrity (Black, 1999:136; Bryman, 2004:509; Cooper and Schindler, 2008:34-46).

Informed consent is obtained prior to any data collection so as not to violate the confidentiality agreement attached with the contract of employment. In performing the tasks, the researcher takes heed to perform in a professional manner in accordance with the code of conduct and practice issued by the Chartered Management Institute (CMI, 2015). For this research, the ethical approval has been applied and approved by NTU on the 14th January 2016 (Appendix 2).

4.5 Research Limitation

In conducting AR, Coughlan and Coghlan (2002) highlighted the threat of validity. However, by adopting the AR cycles, they argued that data validity can be maintained. In this project, the core research group has been setup to provide multiple layers of opportunities to present inferences, viewpoints, and opinions. The purpose is to facilitate transparency, open for testing and critique to maintain validity.

In addition to the issue of validity, research limitation may also arise from quality of relationship (Shani and Pasmore, 2010). To improve the quality of relationship, it is of importance to understand the ethical framework of the company. In addition, the research has to be conducted in accordance to the ethical consideration described in section 3.4.

However, unlike other empirical research where the researcher is 'external' or 'alien' to the company, the researcher is researching in own organisation, which arguably, will have better understanding on the ethical framework and able to make use of the existing quality of relationship to facilitate the research process. It is necessary to be aware of the disadvantages for being over-familiar with the organisation under research. For example, certain processes, practices or issues might be have been too embedded in daily routine or become habitual, which risk being taken for granted, overlooked or lack of objectivity (Coghlan, 2007; Coughlan and Coghlan, 2002; Eden and Huxham, 1996).

In this research, the researcher is new to the company and specifically employed for this project, with the potential to extend employment with Amberol. As a *new employee* in Amberol, it provides the researcher a 'natural position' to engage in the process of emerging enquiry.

With the awareness of political dynamics and the ethical framework (as discussed in section 4.5) within the company, the KTP setting and core groups set up in *Step 1: Construction* provides a lateral and horizontal communication and mediation platform to facilitate this AR project. This platform allows the researcher to practice AR in first, second- and third-person inquiry/practice advocated by Torbert (1998) (Coghlan, 2007).

4.6 AR Quality Plan

As highlighted in section 4.2.5, coming from the paradigm of Mode 2, AR requires its own set of quality criteria. Based on the quality criteria proposed by Coghlan and Brannick (2014). *Table 4.8* below illustrates the quality criteria planned and to be used to guide this research.

Table 4.8 Quality Criteria in AR (Adopted from Coghlan and Brannick, 2014)

	The essence	Rigor	Reflective	Relevant
Purpose and rationale for action and inquiry	• Case for why action and research are necessary or desirable? • What contribution is intended?	• Does it provide a clear rationale for inquiry and action? • To what extent the focus addresses a gap in the scientific literature? • Does it display the data to justify the purpose and rationale for the study?	• Is it linked to past research and scientific literature? • Is it linked to contemporary business and organizational issues?	Does it describe why action is necessary or desirable? (To achieve what for whom)
Response	Section 4.1 – 4.2 Chapter 2 and 3	Chapter 2 and 3	Chapter 3	Section 4.1 – 4.2
Context	Understanding the business, organizational and academic context	Is the contextual data captured in a scientific, systematic and holistic way?	• Does it build on past and present scientific research that is central to the focus of the study? • Does it build on past and present organizational experience that is central to the issue studied?	To what extend relevant analytical framework applied to understand the context?
Response	Chapter 2 and 3	Section 4.3	Chapter 3 and 5	Section 3.8

Methodology and method of inquiry	• The role of the action researcher • Ethical issues • Contracting • Establish learning mechanisms	• To what extent is the process of contracting, selection of methods of action and inquiry collaborative? • To what extend are the methods and inquiry process described with sufficient details? • To what extend are alternative learning mechanisms tapestries explored? • Are appropriate modes of AR selected and justified?	• To what extent are the action and research cycles described? • To what extend is the learning mechanisms tapestry involved in the development of the methodology and inquiry method?	To what extend are the methods of action and inquiry driven by the organization's needs and scholarly criteria?
Response	Section 1.1 Section 4.3 – 4.5	Section 4.1 – 4.5 Chapter 5	Chapter 5	Chapter 2 and 3
Design	• Data collection and generation • Cycles of action research • Building relationships	• To what extend is the project designed and implemented to ensure rigor? • To what extend the data is collaboratively and rigorously generated, collected and explored?	• To what extend is the project designed and implemented collaboratively? • To what extend attention is paid to the development of the quality of the relationship?	To what extend is the research design directed to meet the organization's needs, as well as those of academic rigor?
Response	Section 4.3 – 4.5	Section 4.3 – 4.6	Section 4.3 – 4.6 Chapter5	Chapter 2 Chapter 5 and 6
Narrative and outcomes	Describe the story and outcomes (intended and unintended)	• How well is the story told, with an appropriate level of detail? • To what extend are facts and values distinguished?	To what extend does the story demonstrate collaborative inquiry and action in the present tense?	• To what extend does it captures what happened? • What were the outcomes, both intended and unintended?
Response	Chapter 1 - 7	Chapter 2 and 5	Chapter 4.3 – 4.5 Chapter 5	Chapter 5 and 6

Reflection on the story and outcomes	- Analyse story and reflection - Make judgements on the process and outcomes	To what extend do the narrative and description of outcomes meet the standards/criteria of research?	- To what extend is the story reflected on collaboratively? - To what extend is shared meaning created? - To what extend did dialogue about meaning and possible actions among different organisational groups/units/communities of practice take place?	- To what extent are the story and outcomes' meaning focused on the organization's needs? - To what extend are story and outcomes' meaning focused on addressing the scientific needs?
Response	Chapter 5	Section 4.6 Chapter 5 and 6	Chapter 4.3 – 4.5 Chapter 5	Chapter 5 and 6
Discussion Extrapolation to a broader context. Articulation of practical knowing	- Link story to theory (existing and emerging theory) - Discuss the story and outcomes - Discuss the action research process, quality of relationships and sustainability of the outcomes - Articulate contribution to both theory and practice	To what extend does the entire account (purpose/rationale, methodology and methods, design, narrative and outcomes, reflection, the quality of the action research process, the quality of relationships) contribute to practical knowing?	To what extend does the entire account (purpose/rationale, methodology and methods, design, narrative, outcomes, sustainability of the outcomes and, reflection) fit the quality of the action research process and the quality of relationships?	- To what extend does the entire account (purpose/rationale, methodology and methods, design, narrative and outcomes, reflection) contribute to sustainable outcomes for the organization and practical knowing scholars? - To what extend does the AR approach demonstrate returns that make the process and effort worthwhile?
Response	Chapter 5 and 6	Chapter 5 and 6	Chapter 5 and 6	Chapter 5 and 6

4.7 Summary

In this chapter, Action Research (AR) is found to be the most appropriate research approach to provide the methodological fit in this research project (*Figure 4.10*). *Figure 4.11* illustrates how AR is integrated into the PPC intervention process and *Figure 4.12* shows the position of AR in relation to the conceptual framework developed.

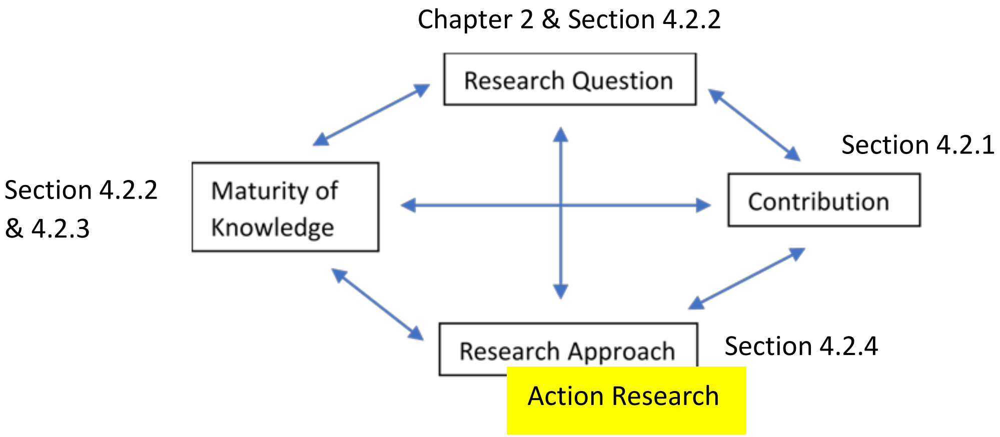


Figure 4.10: Action Research to form Methodological Fit
Source: Ahlstrom, 2016

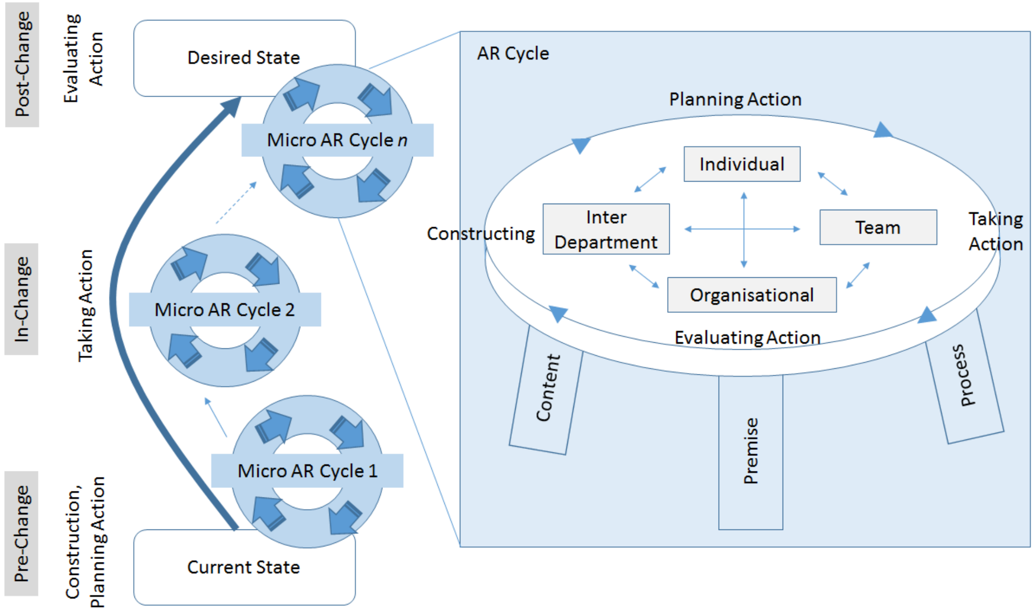


Figure 4.11: Relationship between AR cycles and this Intervention Project

Source: Adapted from Coghlan and Brannick (2012:13)

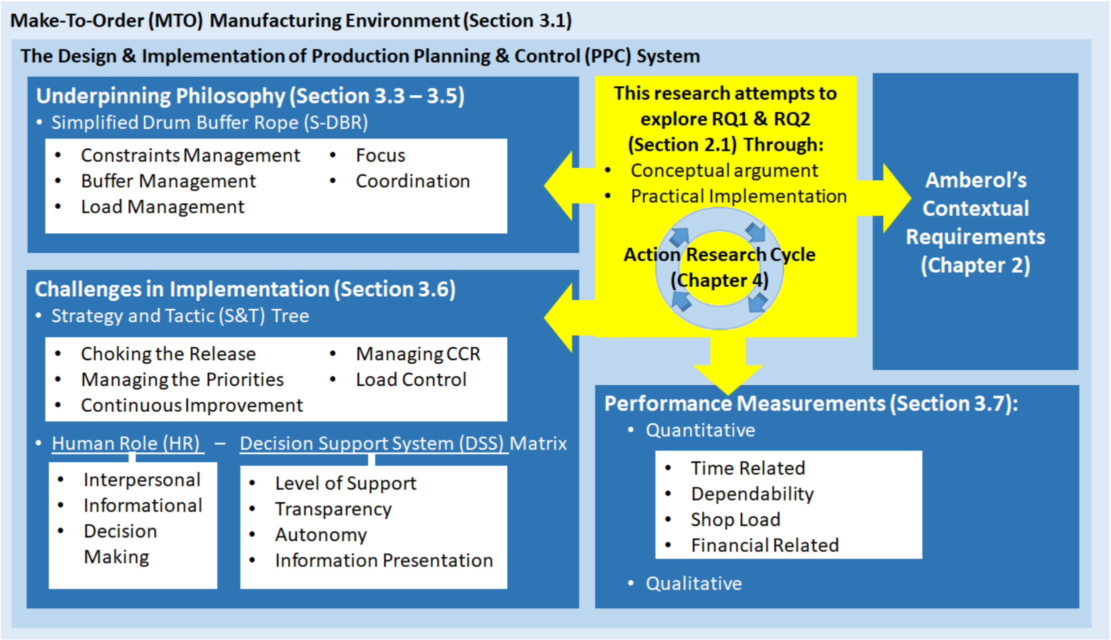


Figure 4.12: Conceptual Framework and the use of Action Research

Chapter 5: Results and Analysis

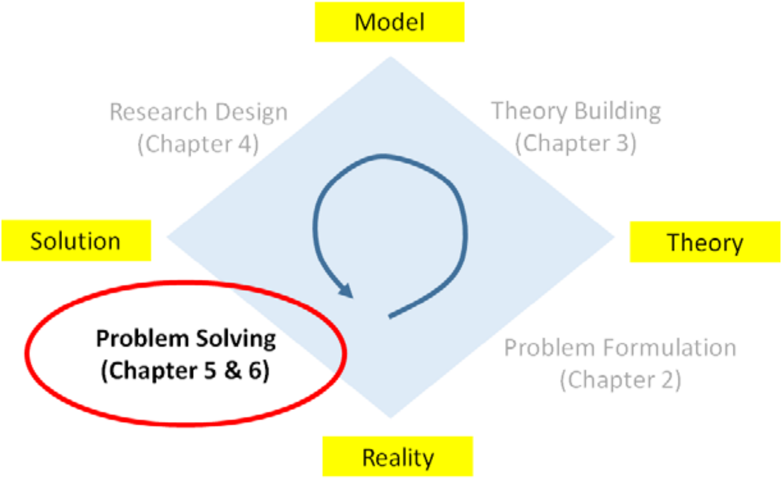


Figure 5.1: Organisation of this Thesis

Source: Adapted from Van der Ven (2007:10)

5.1 Overview

This project commenced in November 2015 and ended in early February 2018, 27 months in total. The additional 3 months (from the originally planned 24 months) was due to the researcher's career advancement. In September 2018, the researcher resigned from the position of Business System Architecture Designer/Programmer to join Nottingham Trent University, two months ahead of the original KTP (Knowledge Transfer Partnership) contract end date. The remaining 2 months equivalent of working days were spread over a period of five months, fulfilled by the researcher on a part time basis. The timeline is illustrated in *Figure 5.2*.

This chapter is structured according to the three phases of the KTP project as designed and discussed in Section 3.3: Pre-Change, In-Change, and Post-Change. Each of this phase corresponds to the over-arching cycle of AR. Within each of these phases, various smaller AR cycles have taken place. For this thesis, only significant AR cycles are selected for discussion.

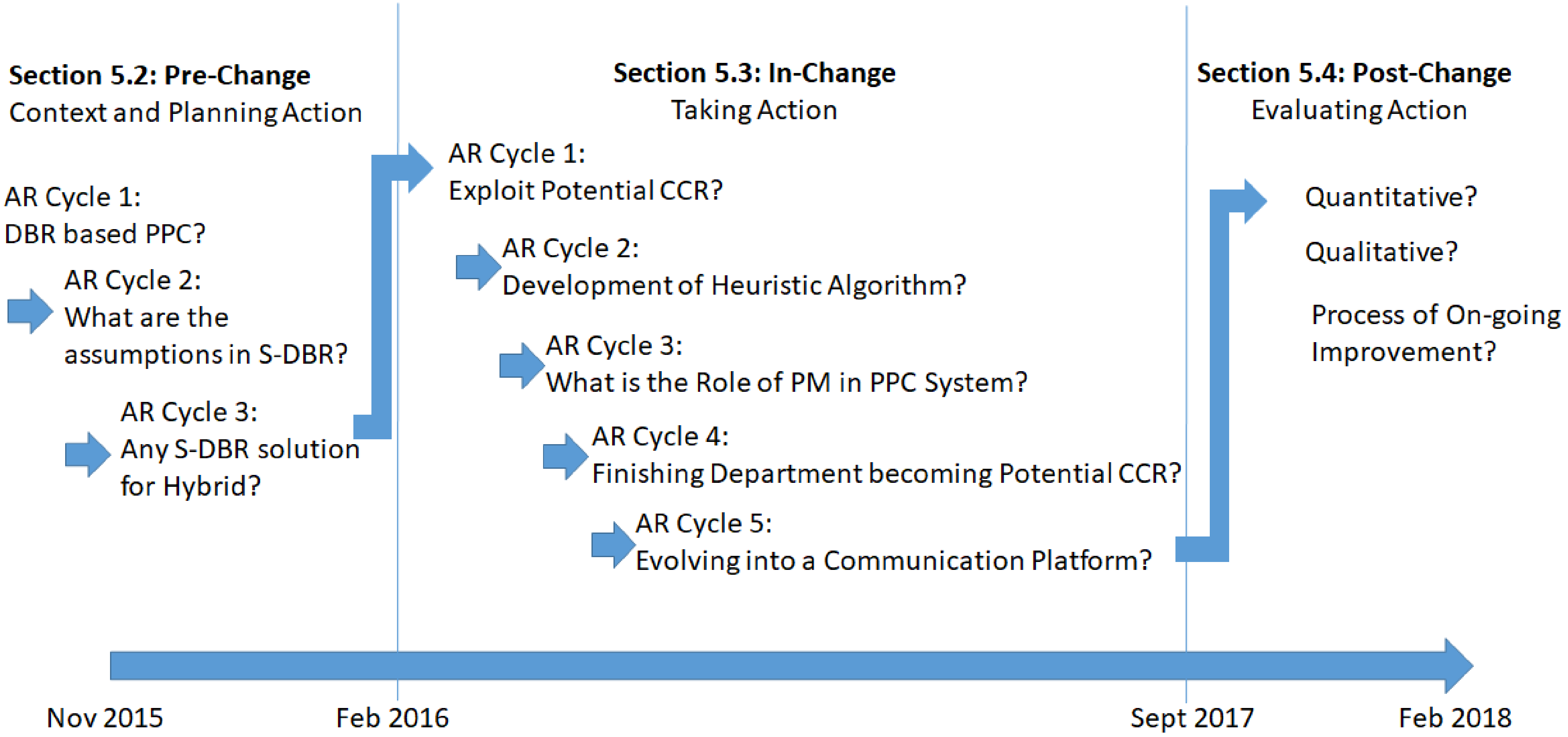
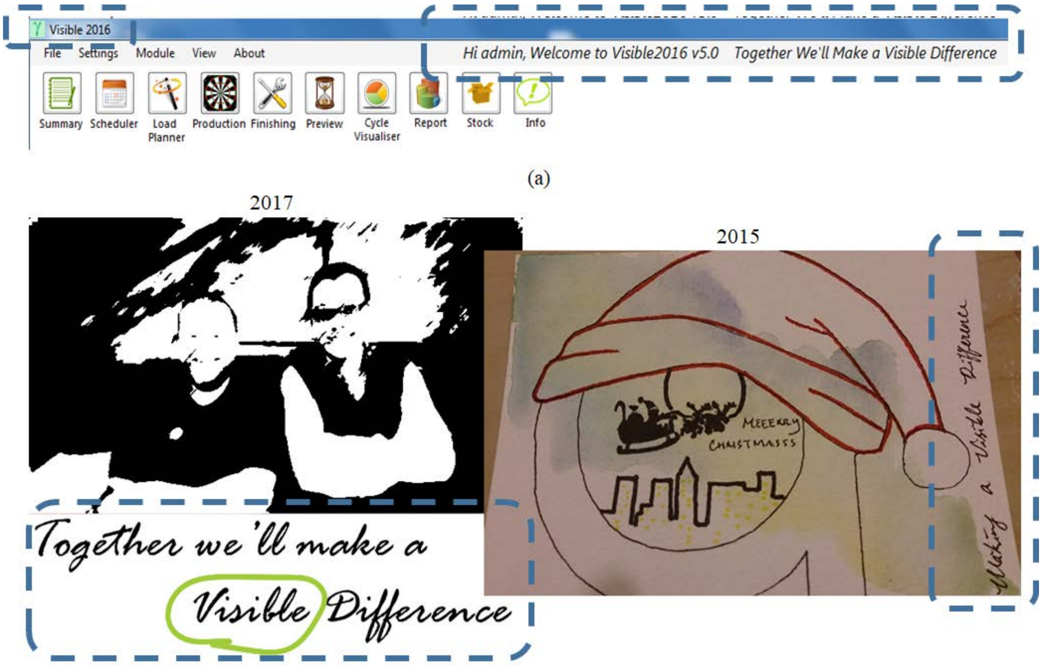


Figure 5.2: Research Timeline

5.1.1 Project Launch

Since the commencement of the KTP project in November 2015, the researcher sought to find a suitable project theme or name. Having gone through the company profile, the tagline of the company is inspirational: ‘***Making a Visible Difference’***. It is the aim of the company to make a visible difference to customers through Amberol’s product. With similar spirit, the aim of the project is to provide a visible difference to the internal operation of Amberol. ***Visible*** was proposed to be used as the project name and was well accepted by senior management.

The company tagline was constantly used by researcher in company’s formal and informal meetings and event, on seasonal greeting cards given to every Amberol’s employee, and on the welcoming page of the software. Referring to *Figure 5.3*, the tagline adopted for the project has evolved to become more inclusive: ‘***Together we’ll make a Visible Difference***’. With the purpose to delivery similar message to Visible’s users, the PPC software developed is named as *Visible*. For the remainder of this document, this software is also referred to as *Visible*.



Hi admin, Welcome to Visible2016 v5.0 Together We'll Make a Visible Difference

(a)

(b)

Figure 5.3: (a) Visible Software; (b) Personalised Seasonal Greeting Cards

5.2 Pre-Change: Context and Planning Action

This section aims to illustrate the preparatory work conducted before actions are taken. Based on the understanding on the contextual manufacturing environment of Amberol, a *fit analysis* is conducted between the contextual environment and the proposed PPC (Production Planning and Control) solution to be adopted: S-DBR (Simplified Drum-Buffer-Rope).

5.2.1 The *Fit* between S-DBR and Amberol

In the original KTP proposal, DBR (Drum-Buffer-Rope) has been proposed to be used to develop a PPC suitable for Amberol. A critical review is done on the application of Theory of Constraint (TOC) for PPC in MTO environment (section 3.3 and 3.4). From the review, it is found that the benefits of S-DBR outweighs DBR. By adopting the DBR – S-DBR comparison table in section 3.3.5, this section will analyse the *fit* of each item in relation to Amberol's contextual environment. The aim is to identify the suitable TOC based PPC approach according to the company's manufacturing environment. The summary is as shown in *Table 5.1*.

Table 5.1: Relevance of Amberol's Manufacturing Environment to DBR and S-DBR

	DBR	S-DBR	**Amberol's Environment**
Constraints Management	System throughput is dictated by internal active CCR Constraint buffer, Shipping buffer and Assembly buffer are deployed to protect CCR Optimised throughput through detailed scheduling	System throughput is dictated by Market Production buffer is used to protect promised delivery due date	In Amberol, the complexity in mould-machine match makes it difficult to determine overall system throughput. As discussed in Section 1.2.2, each match or combination presents different throughput. In addition, other than being MTO, there is peak and off-peak period in Amberol. Thus, it is more practical to use the assumptions in S-DBR, where system throughput is dictated by market.
Buffer Management	Work orders are prioritised according to the percentage of lead time consumption More than one buffer to be monitored, could result in multiple priority list	Work orders are prioritised based on buffer penetration on production buffer with consideration of total touch time (actual time spent on product)	Amberol's production steps are relatively simple. Thus, it is not necessary to deploy multiple buffers: CCR buffer, assembly buffer and shipping buffer. By adopting the concept of buffer aggregation in S-DBR, all

		Only single buffer to be monitored, single priority list	departments are aligned by single priority list.
Load Management	Detailed finite capacity scheduling of the CCR which is to be followed strictly by shop floor.	Monitor Planned Load of potential CCR. Planned Load is used to: i) Determine Material Release Date, ii) Determine Delivery Due Date, iii) Monitor Potential CCR No schedule required. It does not dictate any order sequencing Lead time is anticipated to be shortened due to buffer aggregation Load at potential CCR is 'smoothen' by quoting delivery date according to current loading of potential CCR	The complexity and the high dependency on tacit knowledge in production process makes detailed finite scheduling difficult. In DBR, shop floor personnel are expected to strictly follow system generated CCR schedule. In Amberol, the '*it depends*' nature in production makes strict observation on a fixed schedule impractical. Thus, S-DBR, with the monitoring of potential CCR provides the necessary space for 'tacit knowledge' and 'empowerment' to be exercised.
Focus	Maximum exploitation of CCR with all elements subordinated to it.	Satisfying market demand	Amberol has various forms of buffer capacity which could potentially be deployed. For example, machine, mould, human labour, or time (shift). Thus, the focus of Amberol should be to exploit and satisfy market demand.
Coordination	Assume delivery date is fixed, shop floor. DBR does not explicitly allow due date to be checked without placing an order into the system.	Explicitly includes 'Safe Date' determination for new orders through planned load.	It is anticipated that internal and external coordination of Amberol will be significantly improved. This is made possible through S-DBR which explicitly includes DD determination into the production process, adopting aggregated buffer management system, and offering flexibility through load management monitoring.

As illustrated in *Table 5.1*, S-DBR is more relevant to Amberol's manufacturing environment as compared to DBR. Upon identifying S-DBR as the more appropriate PPC approach, it is necessary to evaluate the relevancy between assumptions used in S-DBR and Amberol's manufacturing environment. This is done by using the assumptions in the generic Strategy and Tactic (S&T) tree for S-DBR. The elements under *3.1.1 Remarkable Due Date Performance* (as shown in *Figure 5.4*) will be used for this analysis. Result of this analysis is presented in a tabular form as shown in *Table 5.2*.

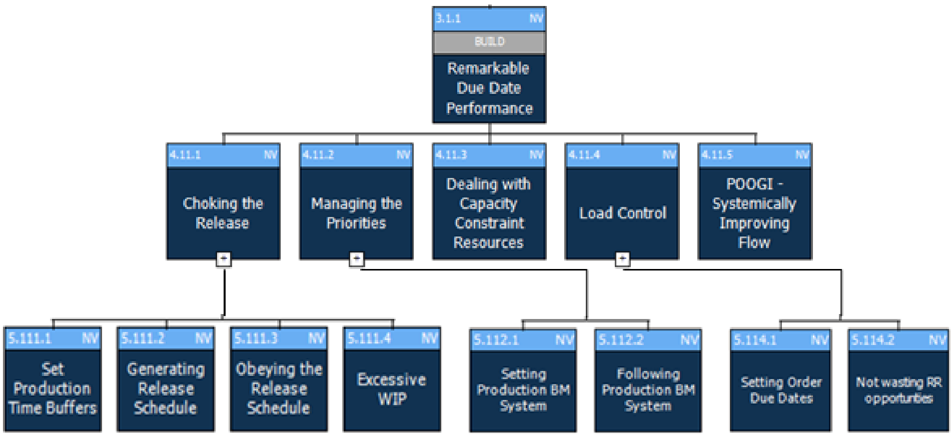


Figure 5.4: Elements under 'Remarkable Due Date Performance'

Table 5.2: Relevancy between S-DBR Assumptions and Amberol's Manufacturing Environment.

Element No.	Assumption	Amberol's Manufacturing Environment
4.11.1 Choking the Release	Traditionally, touch time (actual processing time) is a small faction of the lead time (< 10%). A product spent most of its time in queue.	Touch time is largely significant. This is because manufacturing steps are short and order quantities are small. The only waiting time is due to 'Step 4: Financial Authorisation', which is a 'policy' rather than actual production lead time.
5.111.1 Set Production Time Buffers	Time buffer is set at 50% of production lead time. However, this is not applicable to 'static processes'. 'Static processes' refers to operations which are not able to be shorten.	All operations in Moulding and Finishing Department are 'Static Processes'. The time needed for 'heating' and 'cooling', which is a significant part of the production process is not able to be reduced. Thus, a suitable time buffer has to be designed and deployed.

5.111.2 Generating Release Schedule	Cutting buffer times in half reduces lead times and WIP inventories by one half. Order related data is obtained from existing ERP system.	This is not applicable as both the above elements: 4.11.1 and 5.111.1 does not hold in Amberol. Order related data will be obtained from existing Sage system.
5.111.3 Obeying the Release Schedule		
5.111.4 Excessive WIP		
4.11.2 Managing the Priorities		
5.112.1 Setting Production BM System	Feedback from shop floor on order status/progress is necessary to calculate buffer consumption (or buffer penetration). Robust priority system depends on the information updates from shop floor. Revised priority list according to updated buffer status has to be made known to all departments	Currently, the only feedback mechanism is via job ticket in the form of paper. The update is only done once entire job ticket is completed. There is a need to develop a mechanism to enable frequent two-way communication between 'system' and 'shop floor'.
5.112.2 Following Production BM System		
4.11.3 Dealing with Capacity Constraint Resources (CCR)		
4.11.4 Load Control	DD commitments are given based on actual load	Enquiry system has to be developed
5.114.1 Setting Order Due Dates	DD are given by adding one half of production buffer time to the first available time slot of CCR. CCR is assumed to be located around the middle of the production buffer.	The potential CCR is located in Moulding Department: the 'moulding' process. Instead of being in the middle section of production buffer, the location of potential CCR is at the front end of the production buffer. Finishing department is not

		considered a CCR as its capacity is relatively easier to be increased by increasing man power. It is necesary to redesign the DD determination calculation.
5.114.2 Not wasting RR (Rapid Response) opportunities		
4.11.5 POOGI (Process of On-Going Improvement) – Systemically Improving Flow		

According to the analysis in *Table 5.2*, there are two major assumptions used in S-DBR which Amberol's manufacturing environment does not fit. The two highlighted elements are: *5.111.1 Set Production Time Buffers* and *5.114.1 Setting Order Due Dates*. As the above analysis shows a non-fit between Amberol's contextual environment with the generic S-DBR S&T tree, a further analysis is conducted by referring to existing academic literature.

With reference to the discussion in section 3.3, although S-DBR has been introduced in the practitioner world for almost two decades, it has received relatively low attention from the academia. The journal articles with relevant empirical cases are: (i) Hwang et al. (2011), (ii) Allison et al. (2012), and (iii) Benavides and Landeghem (2015). From the three articles available, only (i) and (iii) explicitly discuss the implementation process with reference to the five implementation elements in S-DBR S&T (refer to section 3.3.6 and section 3.3.2). Among the two journal articles, (iii) is the most recent publication with inter-case analysis between four case companies.

By building upon the original table used by Benavides and Landeghem (2015), the characteristics of case company from Hwang et al. (2011) and Amberol is added and shown in *Table 5.3*. The four cases from Benavides and Landeghem (2015) are labelled as Company A, B, C, and D, whereas case company in Hwang et al. (2011) is labelled as Company E.

In evaluating the production characteristic, Amberol presents a more complex manufacturing environment then prior case study. The production in Amberol is non-repetitive, where resources are heavily shared for various products. In addition, the products require substantial customisation, where colour and in-mould graphics have to be determined before the start of the production process. This brings in the third aspect, where production routing in Amberol is more dynamic as compared to prior ‘line flow’ cases. Amberol’s products also exhibits additional complexity where they are multi-levels and require assembly process, whereas it is single-level for other case companies. Additional challenge to the PPC system design also arises from the complexity in parallel machine/mould loading highlighted in section 2.2.

Apart from the additional complexity in production characteristics, Amberol does not fit most of the necessary assumptions in S-DBR. Compared to prior reported case companies, the touch time in Amberol is significant. In addition, there is possibility of more than one bottleneck. This brings in the third difference between Amberol and prior case companies, which is the existence of wandering bottleneck in this research. The other non-conventional S-DBR compliant characteristic found in Amberol is the location of potential CCR in the process route. Instead of locating towards the middle of the process route, it lies at the front, the first workstation. The *non-fit* in S-DBR assumptions prompted necessary *re-think* and *re-design* based on the original philosophy of TOC and S-DBR. The details will be discussed in next section: 5.2.2.

Table 5.3: Summary Table for Comparison between 6 Case Companies

Authors/ Source	Benavides and Landeghem (2015) and Buestan (2015)				Hwang et al. (2011)	This research
	Company A	**Company B**	**Company C**	**Company D**	**Company E**	**Amberol**
General Characterisation						
Product	Plastic bags	Plastic bags	Medals	Offset printing	Furniture	**Plastic products**
No. of employees	75	130	40	105	5000	**25**
Production strategy	98%MTO, 2%MTS	90%MTO, 10%MTS	95%MTO, 5%MTS	100% MTO	MTO & MTS	**100% MTO**
Repetitiveness level	Almost all repetitive	Almost all repetitive	Almost all repetitive	At least 75% not repetitive	unknown	**Non-repetitive.**
Order winners	Delivery	Quality	Delivery	Delivery and price	Delivery	**Delivery and Quality**
Product Characterisation						
Product structure	Single level	Single level	Single level	Single level	Multilevel	**Multilevel**
No. of families	4	4	3	15	unknown	**Not applicable**
Level of customisation	Standard components are combined	Standard components are combined	Standard components are combined	Customised	Standard components are combined	**Semi-customised products**

S-DBR Applicability/Assumptions						
Touch Time <10%	fit	fit	fit	fit	fit	**Not fit, >10%**
Number of CCRs	1	1	1	1	1	**Possibly >1**
Wandering bottleneck (potential CCR)	Stationary	Stationary	Stationary	Stationary	Stationary	**Wandering between mould/machine**
Sequence Independent at CCR	Moderately affect	Independent	Moderately Independent	Independent	Independent	**Highly dependent**
Location of CCR	Front	Middle	Front	Middle	Unknown	**Front**
S-DBR S&T Implementation Elements: Element 1: Choking the Release						
5.111.1 Production Buffer (PB) to be 50% of original lead time	Implemented	Implemented	Not implemented	30%	Around 30%	
5.111.1 Different PB are created when difference between PB is larger than one quarter	One PB per family	Single PB	Single PB	One PB per family	Each factory chooses single PB according to the product which requires longest touch time.	
5.11.3 Release schedule is effectively followed	95%	99%	95%	80%	Implemented	
Element 2: Managing the Priorities						
5.112.1 Current buffer status is available and visible to necessary departments	Supported by software with LCD display, coloured tags and integrated report among departments	Supported by software with LCD display and integrated report among departments	Supported by software with board display and integrated report among departments	Supported by software with LCD display and integrated report among departments	Management by sight. Supported by colour coded workshop job transfer zone. Work orders with Red or Black are manually recorded and displayed on black board.	
5.112.2 BM is the only priority system	Additional sequencing rules subordinated to BM priorities	Fully implemented	Fully implemented	Additional sequencing rules subordinated to BM priorities	Fully implemented	
5.112.2 Management does intervene BM priorities	Occasionally intervenes	No intervention	No intervention	Occasionally intervenes	No intervention	
Element 3: Dealing with CCR (Capacity Constrained Resources)						
4.11.3 CCRs are identified	Reactive approach to identify emerging CCRs based on buffer consumption	Formal procedure monitors workload resources weekly	Formal procedure monitors workload resources weekly	Reactive approach to identify emerging CCRs based on buffer consumption	unknown	
4.11.3 Trial period before rolling out reliability offer	Not implemented	Not implemented	Not implemented	Not implemented	unknown	

Element 4: Load Control						
5.114.1 DD (Due date) set according to first available slot on CCR plus ½ PB.	Full PB is added because CCR is located on the front end of routing	½ PB added as CCR is located in the middle of routing	Full PB is added because CCR is located on the front end of routing	½ PB added as CCR is located in the middle of routing	Unknown	
5.114.1 DD is generated in less than 1 min	Fully implemented	Fully implemented	Fully implemented	Fully implemented	Unknown	
5.114.1 Sales force is trained to call operations before committing to client	Fully implemented.	Fully implemented.	Fully implemented.	Sales force is not subordinated to operations	Unknown	
5.114.2 Not giving shorter delivery lead time (DLT) for free	Fully implemented. Orders with shorter DLT are charged	Fully implemented	Fully implemented. Orders with shorter DLT are charged	Partially implemented. Top management intervenes to offer orders shorter than DLT.	Unknown	
Element 5: POOGI (Process of On-Going Improvement)						
4.11.5 Causes of non-trivial disruption (1/10 of PB delay) is reported and stored	Fully implemented	Fully implemented	Fully implemented	Fully implemented	Unknown	
4.11.5 Formal procedure is established to analyse causes of disruptions	Not implemented	Fully implemented	Partially implemented. Weekly meetings are held to analyse causes. No monitoring	Not implemented	Unknown	
4.11.5 All corresponding causes for 'Red' are analysed	Not implemented	Not implemented	Not implemented	Not implemented	Unknown	

5.2.2 Redesign of Time Buffer and Due Date Determination

With reference to *Table 5.3*, elements 5.111.1 (Time Buffer Setting) and 5.114.1 (Setting Due Date) does not form a fit with contextual environment. A revisit of existing literature is done by members in Group 2 (set up in Section 3.3.2) to inform any adaptation or redesign work necessary.

Literature review is conducted to explore existing knowledge on S-DBR implementation in manufacturing environment with significant touch time (also known as high touch time) and potential CCR location which is not in the middle of production route. With reference to the discussion in section 3.3.3 and section 3.3.7, the issue of potential location of CCR has been discussed by both practitioners and academics. However, the solution suggested is with the assumption of insignificant touch time (Schragenheim et al., 2009; Lee et al., 2010). Thus, it might not be entirely suitable to Amberol's contextual environment.

A possible solution highlighted in section 3.3.7 is the 'linear high touch time' solution proposed by Scheinkopf et al. (2012) and Inherent Simplicity (2010). Both solutions required buffer redesign based on hybrid between project management and manufacturing. For the above solution to work, both suggested the adoption of frequent work order progress feedback into the system. Adopting similar concept, the remainder of this section will illustrate the time buffer design for Amberol.

Time Buffer Size

There are two standard lead time used by Amberol: 3 weeks for planters and 4 weeks for bins. This was done with buffers allocated for both Moulding and Finishing Departments. To avoid Parkinson's Law, the phenomena '*where work expands so as to fill the time available for its completion*' (Parkinson, 1955), buffers from both departments are aggregated towards the end of the production process, as depicted in *Figure 5.5*. Instead of having two separate lead time, the PPC will adopt single time buffer size of 3 weeks. The benefit of aggregating buffer towards the end is to avoid wasting resources. Moreover, resources masked by Parkinson's Law will be exposed. Through buffer aggregation, buffer deployed could be effectively utilised to protect against variation and uncertainties. Coupled with the buffer status (BS) and buffer consumption concept in S-DBR, work orders can be managed via buffer management (BM) concept in S-DBR.

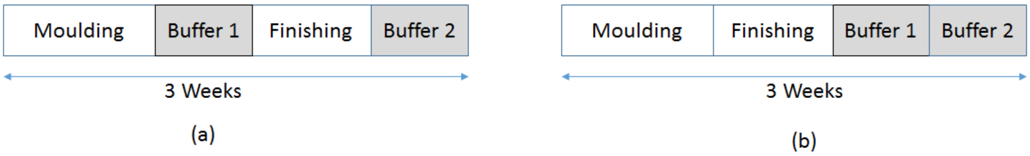


Figure 5.5: (a) Before: Distributed Buffer; (b) After: Aggregated Buffer

Buffer Management

Rather than dividing the whole 3 weeks (15 working days) buffer into the conventional three colours of 1/3 each, a 'pooling' stage is explicitly introduced as illustrated in *Figure 5.6*. Job tickets which falls under 'pooling' are not required to be released.

With the consideration that most of the orders in Amberol are small in quantities, PM inclines to 'group' and produce similar mould products in batches. However, it is difficult to visualise and make an informed decision between grouped batch size and DD performance. By introducing a 'pooling' stage, it explicitly allows a period to aggregate and produce similar products in batch. It also avoids redundant machine setup time.

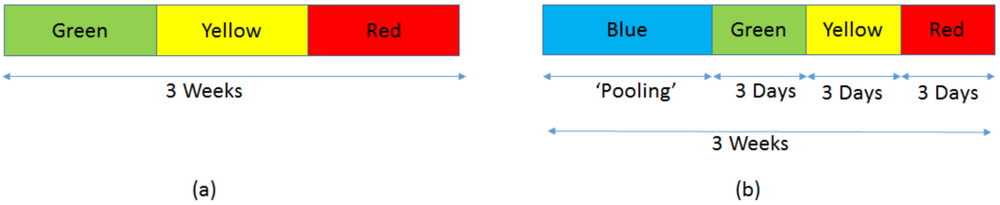


Figure 5.6: (a) Conventional BM; (b) New BM for Amberol

With the adoption of 'pool' concept in WLC discussed in Section 2.4, postponing the release of job offers additional protection buffer against uncertainties such as changes or cancellation of orders. In addition, it reduces the number of work-in-progress (WIP) on the shop floor, allowing system to be more responsive towards urgent jobs. The remaining colours bear similar meaning and functions as the conventional BM discussed in section 3.3.4. As there are no rules to guide the number of days for pooling. For convenience of calculation, pooling time is trialled for 6 days. The remaining 9 days are allocated for green, yellow and red region with 3 days for each region. As discussed in section 3.3.4, the buffer size could be further refined according to manufacturing environment.

Due Date Determination

To determine DD in the stage of Step 1: Customer Enquiry, and Step 2: Order Generation, total touch time, T (in minutes), required for a product is determined as shown in Equation (5.1) where t_m is the touch time required for Moulding department; t_f is the touch time required for Finishing department; and n is the quantity ordered.

$$T = (t_m + t_f) \times n \qquad (5.1)$$

Total touch time, T, is then added to the first available time slot of the potential CCR. In this case, as discussed in *Table 5.4*, the potential CCR is identified as the moulding stage. To cater for the need of a machine-mould match, the first available time slot has to be the latest available time slot between machine and mould as shown in *Figure 5.7*. In (a), the first availability time slot of Machine: t_2 is utilised; In (b), the first availability time slot of Mould: t_2 is utilised. In (c), as both the first availability time slot of Machine and Mould are the same, either one can be used.

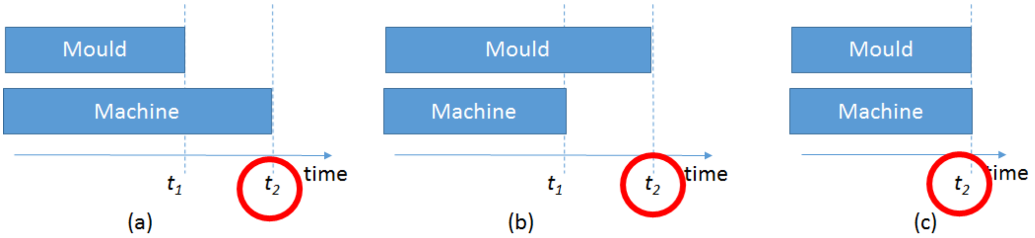


Figure 5.7: Illustration on First Available Time Slots of Mould and Machine

The Provisional due date, DD_P, is determined by adding total touch time, T, to the first available time slot. In this example, t_2 is added as shown in Equation (5.2) below.

$$DD_P = T + t_2 \qquad (5.2)$$

Upon determining provisional due date, DD_p, using standard lead time of 3 weeks, buffer penetration, BP (in percentage), is determined by utilising Equation (5.3):

$$\%BP = \frac{DD_p}{DD_s} \times 100\% \qquad (5.3)$$

where T is the total touch time required, and DD_s is the due date computed by adding 3 weeks from 'today', as illustrated in *Figure 4.7*.

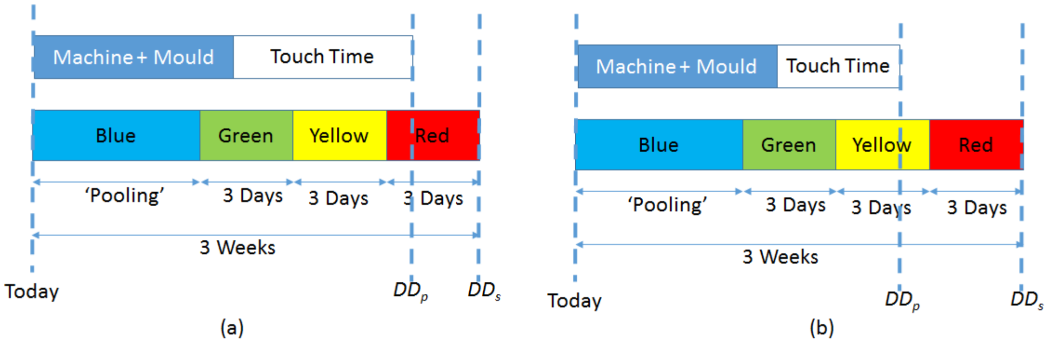


Figure 5.8: Due Date Determination (a) %BP > 80%; (b) %BP ≤ 80%

To determine the final due date, DD, two scenarios are introduced based on the $\%BP$ computed using Equation (4.6). If $\%BP$ is less than 80%, which is not in yellow zone or below, DD_s will be used as the final due date. However, if $\%BP$ is greater than

80%, which enters the red zone or beyond, final due date is determined by adding 5 working days to the provisional due date, DD_p. This is expressed in Equation (5.4) below.

$$DD = \begin{cases} DD_s,\ if\ \%BP \leq 80\% \\ DD_p + 5\ \ if\ \%BP > 80\% \end{cases} \qquad (5.4)$$

By introducing the new rule, Amberol is able to maintain the original standard lead time. For orders where *%BP* enters red zone, an additional buffer of 5 working days is added to protect against variability and uncertainties. There are no particular *rules* in the determination of the number of days. The following are some considerations.

- With reference to Element 5.111.1 in the S&T for S-DBR as shown in *Table 4.7*, it is advisable to use single buffer unless there is significant difference in production lead time between products. To keep it simple, the proposed 9 days buffer will be used.
- As discussed in section 3.3.4, it is desirable for majority of the orders to complete in the Yellow zone. By adding 5 days, it places the buffer status of an order to between mid-Green and mid-Yellow zone. With most orders in small quantities, 5 days provides adequate buffer size.
- If an order is very large, the BM is adequate to provide early alert. The relatively long remaining lead time allows management to intervene.

Consideration for Assembly Products

In Amberol, there are products which require multiple moulded parts. These parts require different parts where each has different machine/mould requirement and thus different touch time during moulding stage. The most complex assembly product requires fifteen moulded components. Managing each component according to individual production requirement might cause required assembly parts to release too late into the system. As shown in *Figure 5.8*, different processing time for components A, B, and C generates different release priority based on BS. As a result, component B is not ready at time, t_f. According to DBR practice discussed in section 3.3.4, an assembly buffer is necessary to ensure all components are available without delaying assembly start time.

Considering the number of moulded components is relatively small and the limited capacity of assembly department, a simplified solution is proposed to be used. This simplified solution involves utilising similar time buffer size, buffer management and due date determination mechanism discussed above.

At planning stage, all moulded components in an assembly product is treated as individual moulded product. Due date for assembly product is determined by referring to the moulded component which requires the longest processing time. This due date is shared by all moulded components. Acknowledging that all moulded parts need to be available before assembly work could begin (also known as 'full kit'), without further complicating the above mechanism, the longest time required post moulding is used for all moulded components.

Referring to *Figure 5.9*, Component C has the longest post moulding processing time, F_C. This is added to the processing time for both Component A, and B, replacing the original F_A and F_B. This automatically align release date according to the 'full kit' requirement. Instead of having separate buffer, it is anticipated that aggregated buffer is adequate to provide the necessary feedback signal to manage the priority of all moulded components.

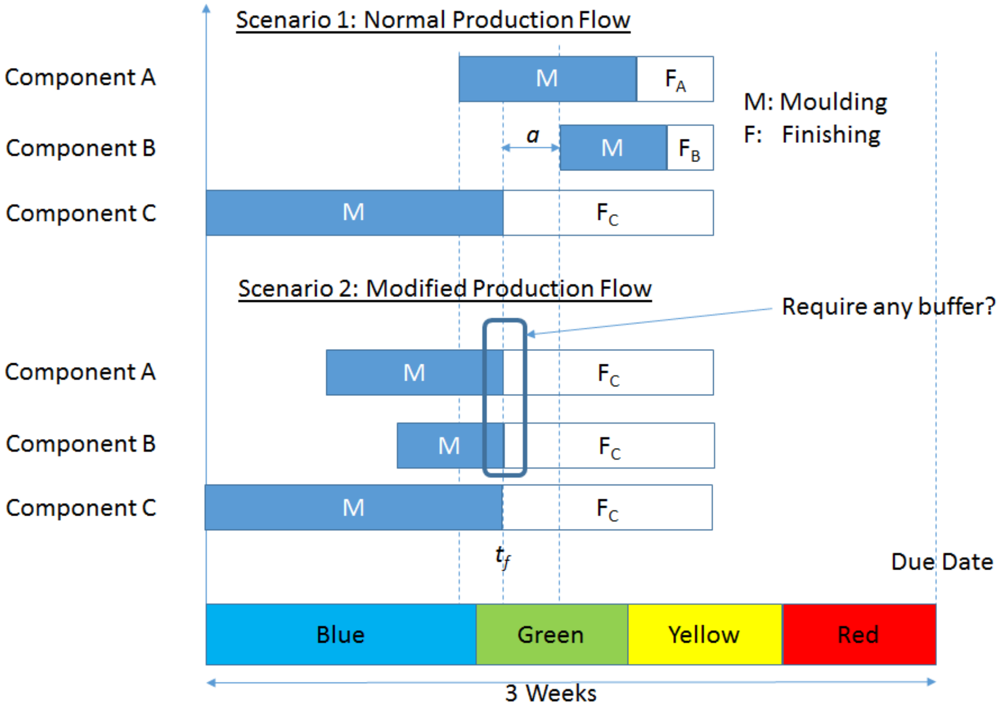


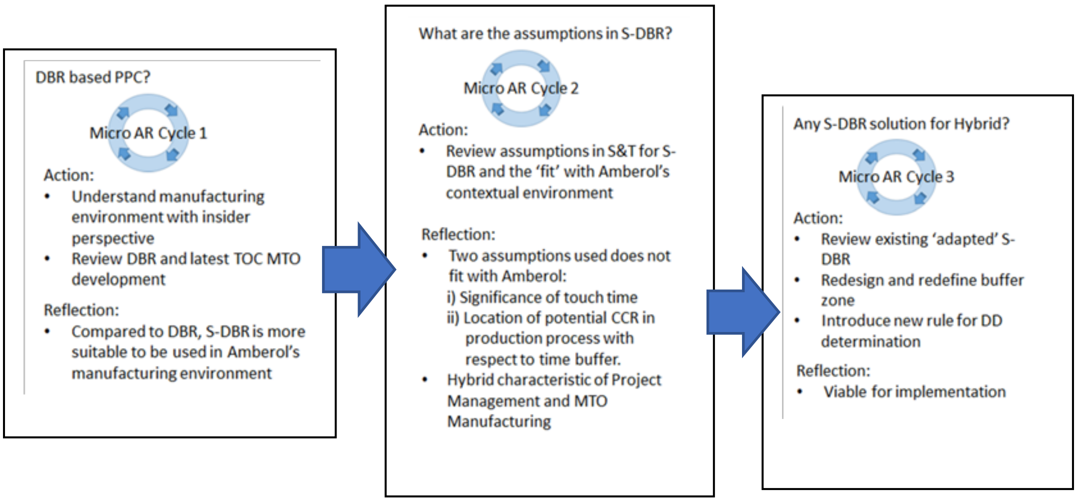
Figure 5.9: Consideration on Assembly Product

5.2.3 Summary

From the above discussion, multiple reflection cycles have taken place. As depicted in *Figure 5.10*, it started by challenging the suitability of DBR and S-DBR as a PPC system (2ection 3.3 and 3.4). By adopting the comparison criteria established in section 3.3.5, *Table 5.1* provides an analysis which shows S-DBR being the more appropriate approach in Amberol.

Next, the fit between S-DBR and Amberol’s contextual environment is evaluated. The assumptions used by practitioners in S-DBR implementation is drawn from the Strategy and Tactic (S&T) Tree, whereas the contextual manufacturing environment of Amberol has been detailed in chapter 2. This evaluation result presented in *Table 5.3* shows misalignment in two assumptions: the significance of touch time and the location of potential capacity constraint resources (CCR).

Drawing from existing literature, buffer size and the mechanism to determine due date is redesigned and ready to be tested.


DBR based PPC?

Micro AR Cycle 1

Action:
- Understand manufacturing environment with insider perspective
- Review DBR and latest TOC MTO development

Reflection:
- Compared to DBR, S-DBR is more suitable to be used in Amberol’s manufacturing environment

What are the assumptions in S-DBR?

Micro AR Cycle 2

Action:
- Review assumptions in S&T for S-DBR and the ‘fit’ with Amberol’s contextual environment

Reflection:
- Two assumptions used does not fit with Amberol:
  i) Significance of touch time
  ii) Location of potential CCR in production process with respect to time buffer.
- Hybrid characteristic of Project Management and MTO Manufacturing

Any S-DBR solution for Hybrid?

Micro AR Cycle 3

Action:
- Review existing ‘adapted’ S-DBR
- Redesign and redefine buffer zone
- Introduce new rule for DD determination

Reflection:
- Viable for implementation

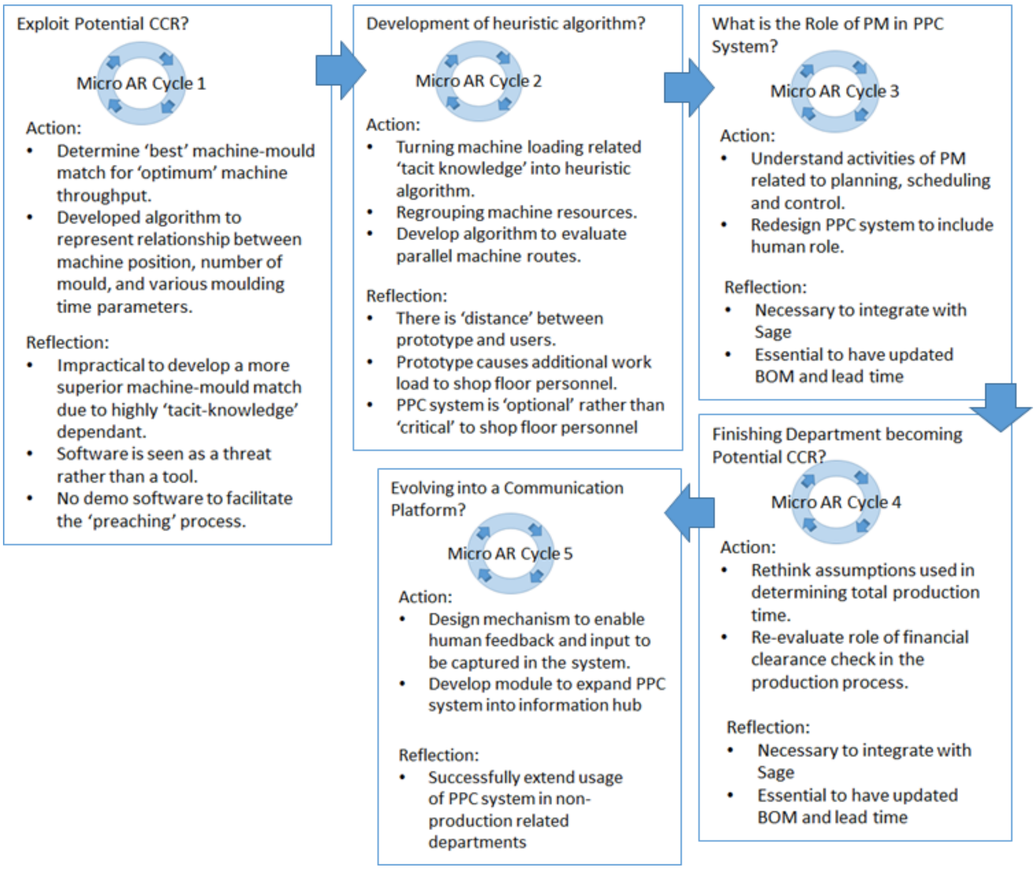
Figure 5.10: AR Cycles in Pre-Change stage

Table 5.4: Key Points Identified in the Development of a S-DBR based PPC Decision Support Tool for Amberol

	Level of Support	**Transparency**	**Autonomy**	**Information Presentation**
Interpersonal	• Should not be adding complexity and burden to existing workload. • Should be an integral part of day-to-day activity. • Facilitate communication	• Support personnel performance evaluation	• Encourage team work • Allow higher management to provide empowerment	• Dashboard • Graphical/Visual • Easy to understand • Easy to navigate • Job priorities are represented using five colours: *(i) blue*: to be pooled *(ii) green*: could choose to start if no other jobs which are more urgent *(iii) yellow*: start job *(iv) red*: expedite job *(v) black*: late
Informational	• Information on all job tickets in hand (In-Progress and In-Queue) • Auto-resource allocation (under normal condition) • Resource Utilisation • Workload per Standard Industrial Lead Time • Job Ticket Priority • Due date for confirmed orders to be based on current system loading • Job ticket status and progress • Allow proposed due date to be enquired based on current system loading • Allowed centralised work order information to be captured and shared on single platform by all departments	• Easy to understand PPC principles: *Time Buffer Management* for job priority • User defined Resource Loading algorithm • User defined Performance Target • User defined touch time (rough cut actual time worked on an item) • Product related Information/knowledge can be easily updated and proliferated	• Allow manipulation of capacity options/variables to simulate outcome: - Machines deployed - Machine performance - Additional mould deployment - Batch size • Information source traceability	
Decision Making	• To *Prioritise* • To *Expedite* • To *Escalate* if need higher management's attention • To *Target* areas requiring continuous improvement	• Allow final resource assignment • Allow rescheduling		

5.3.7 Summary

From the above discussion, various AR micro cycles have taken place in the second stage of this research project. *Figure 5.35* shows a summary of AR cycles involved in 'In-Change' phase. Having implemented Production, Planned Load and Preview modules for one year, section 5.4 will discuss the 'Post-Change' evaluation.



Exploit Potential CCR?

Micro AR Cycle 1

Action:
- Determine 'best' machine-mould match for 'optimum' machine throughput.
- Developed algorithm to represent relationship between machine position, number of mould, and various moulding time parameters.

Reflection:
- Impractical to develop a more superior machine-mould match due to highly 'tacit-knowledge' dependant.
- Software is seen as a threat rather than a tool.
- No demo software to facilitate the 'preaching' process.

Development of heuristic algorithm?

Micro AR Cycle 2

Action:
- Turning machine loading related 'tacit knowledge' into heuristic algorithm.
- Regrouping machine resources.
- Develop algorithm to evaluate parallel machine routes.

Reflection:
- There is 'distance' between prototype and users.
- Prototype causes additional work load to shop floor personnel.
- PPC system is 'optional' rather than 'critical' to shop floor personnel

What is the Role of PM in PPC System?

Micro AR Cycle 3

Action:
- Understand activities of PM related to planning, scheduling and control.
- Redesign PPC system to include human role.

Reflection:
- Necessary to integrate with Sage
- Essential to have updated BOM and lead time

Finishing Department becoming Potential CCR?

Micro AR Cycle 4

Action:
- Rethink assumptions used in determining total production time.
- Re-evaluate role of financial clearance check in the production process.

Reflection:
- Necessary to integrate with Sage
- Essential to have updated BOM and lead time

Evolving into a Communication Platform?

Micro AR Cycle 5

Action:
- Design mechanism to enable human feedback and input to be captured in the system.
- Develop module to expand PPC system into information hub

Reflection:
- Successfully extend usage of PPC system in non-production related departments

Figure 5.35: Summary of AR cycles in 'In-Change' Phase

5.5 Summary

This chapter demonstrated the successful implementation of an S-DBR based PPC Decision Support System: Visible, in Amberol. On the one hand, there is the over-arching phases which provides the overall project structure of Pre-Change, In-Change and Post-Change. On the other hand, there are various AR cycles in each phase which contributes towards the success of the implementation. The integration of Visible into Amberol's business process (as shown in *Figure 5.38*) has also prompted reflection and 're-think' to utilise Visible to contribute towards maintaining its existing BSI (British Standards Institution) standards.

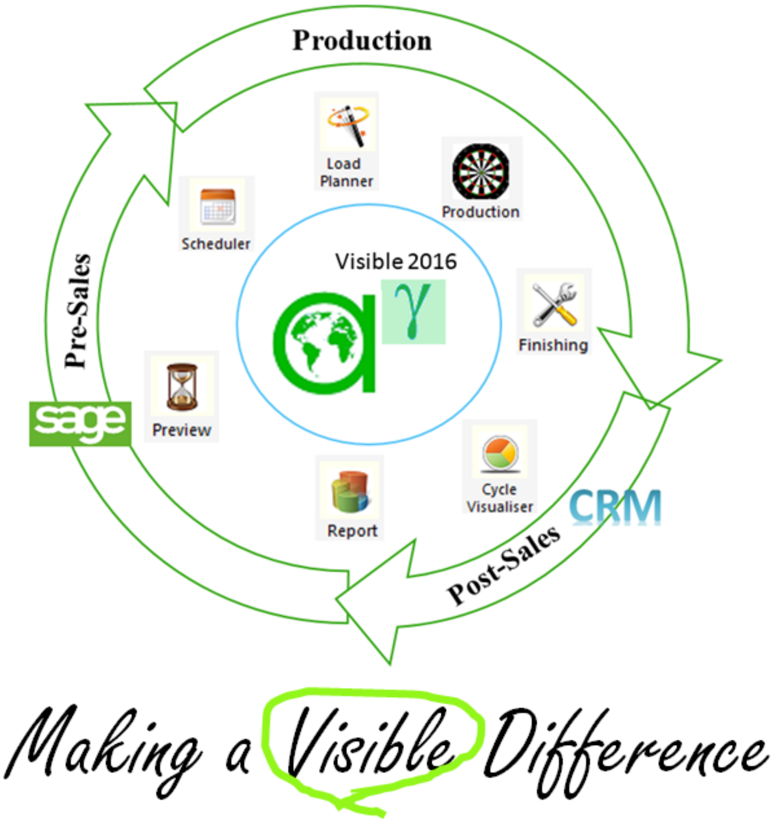


Figure 5.38: Position of Visible in Amberol's Business Process

Chapter 6: Research Impact

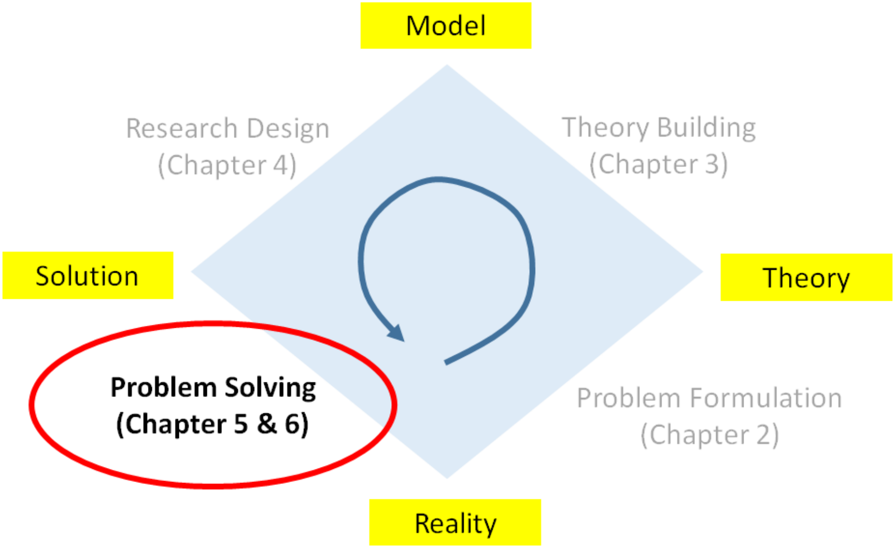


Figure 6.1: Organisation of this Thesis

Source: Adapted from Van der Ven (2007:10)

6.1 Overview

This chapter serves as a continuation of section 5.4. In section 5.4, the evaluation concentrates on the impact of the research on Amberol itself. This chapter is to evaluate the wider impact of this research. As highlighted in section 4.2, the contribution of this research is twofold. Through the development of a solution to solve the *real-life* problem, the objective is to contribute towards both theory and practice. Thus, the wider impact of this research will be evaluated by drawing from the previous chapters: literature review, research methodology, and results and analysis.

This chapter is structured as follows. It begins with an evaluation on the impact of this research towards the existing Simplified Drum-Buffer-Rope (S-DBR) theory and practice. This evaluation is conducted by presenting the contribution of this research towards the S-DBR implementation related knowledge captured in existing academic publication, as analysed in section 5.2.1. In addition, based on the generic S&T (Strategy and Tactic) tree for S-DBR, an S&T tree is developed for Amberol. The contribution of this research is further highlighted by placing both the generic and contextual S&T tree side by side.

The subsequent focus of evaluation is placed on the potential contribution of this research to other Make-To-Order (MTO) Production Planning and Control (PPC) approaches Work Load Control (WLC). As discussed in section 3.2, WLC is advocated as the most suitable MTO PPC approach by academia. Apart from the afore-mentioned contribution towards the *hard* part of PPC, this research potentially highlighted the essential role of human factor in the practical implementation of PPC. Through the use of action research (AR) as research approach in this research, it potentially contributes by providing an additional AR research case in PPC research.

6.2 S-DBR

6.2.1 '*Standing on the Shoulders of Giants*'

To evaluate the impact of this research on S-DBR, it is necessary to revisit the perspective of Theory of Constraints (TOC) on PPC. As discussed in section 3.3.2, there are two main perspectives: (i) the concept of 'flow' and (ii) the balance between *planning* and *execution*. The common trait between both perspectives is the emphasis on *practicality* in the *mechanisms* developed. This is in line with the discussion in section 3.3.2, which highlighted the conclusion by Goldratt (2009) in reviewing the production system introduced by Ford and Ohno. This conclusion is encapsulated in the following four concepts:

(i) The primary focus of operations is to improve flow,
(ii) This is realised by the deployment of a practical mechanism to control against overproduction,
(iii) In the process of deployment, local efficiencies have to be abolished, and
(iv) A mechanism to balance flow is necessary for continuous improvement.

The four concepts above advocate the need to develop practical mechanism to realise 'control' mechanism based on the concept of flow. The practical mechanisms used in both Ford and Toyota production systems are highlighted by Goldratt as 'space' by Ford and 'inventory' by Ohno. For MTO manufacturing environment, he proposes the use of 'time' as the mechanism to be used as the practical mechanism.

Adopting similar approach, the Visible software developed for Amberol is developed based on the platform provided by S-DBR. This revolves around the three pillars discussed in section 3.3: Constraints Management (CM), Buffer Management (BM), and Load Management (LM). Due to the *mismatch* between Amberol's contextual environment and the assumptions used in S-DBR (as shown in Section 5.2.1 and *Table 5.2*), necessary adaption has to be done. The characteristics found in Amberol includes significant touch time, multiple Capacity Constraint Resources (CCR), non-static CCR, heavily shared resources, involvement of assembly, and parallel machine routing. Although these implementation issues have been raised by both practitioners and researchers, limited attention has been given in S-DBR academic literature (section 3.3.7).

As illustrated in Chapter 5, through the AR cycles, this research provides additional insights into the applicability of S-DBR concept and a practical mechanism to implement S-DBR in such manufacturing environment. The discussion on the contribution of this research to S-DBR will begin by comparing the S-DBR implementation knowledge captured in this research with the existing literature in academia. This will be discussed in section 6.2.2 by using the generic S-DBR S&T tree as a reference.

6.2.2 Generic S-DBR S&T tree

In section 5.2.1, through *Table 5.3*, an evaluation is done on existing S-DBR literature in academia to inform the implementation of S-DBR in Amberol. However, the existing S-DBR case studies reported in academia demonstrates *fit* with the assumptions laid out in generic S-DBR S&T tree. In addition, the cases do not possess the S-DBR implementation challenges highlighted by practitioners. This includes multiple CCRs, wandering CCR and sequence dependent CCR as discussed in section 3.3.7. By using the five elements in generic S-DBR S&T tree, this discussion will highlight how these challenges are addressed in Amberol.

Element 1: Choking the Release

In Amberol, as the position of potential CCR lies at the front of the process route, it forms a natural choking mechanism to the system. However, as the touch time is significant, it is necessary to re-think how release schedule is determined. In conventional S-DBR, production buffer (PB) is taken to be half of the original lead time. Delivery Date (DD) is determined by adding half of Production Buffer (PB) to the first available slot of potential CCR. Work order release date is determined by subtracting half of PB from first available time slot of potential CCR (section 3.3.5). However, the above practice is only valid with the assumption that the potential CCR is in the middle of the process routing. In addition, the work order sequence must be insignificant. This requires the work order touch time to be insignificant and its sequence to be independent at potential CCR. With the above assumptions and the use of Buffer Status (BS) to monitor work order priority, there is adequate time to 'make up' for the losses incurred due to sequencing choices. The above mechanism can achieve 'flow' with minimum focus on 'planning' but higher emphasis on 'execution'.

In Amberol, the production characteristic demonstrates significant touch time. In addition, the CCR throughput is dependent on product sequence or setup. Thus, it is necessary to utilise detailed work order scheduling and sequencing. However, due to the complexity of machine/mould match in Amberol, as demonstrated in section 5.3.3, while developing work order sequence, a balance must be struck between practicality and the exploitation of potential CCR for higher throughput performance.

The heuristic algorithm developed through action research (AR) cycles is perceived to be *practical* by Amberol. As the potential CCR lies at the front of the process route, the release decision can be based on the priority of the work order obtained through BS. This leads towards the discussion of second element: Managing the Priorities. A summary on contribution to *Element 1* is shown in *Table 6.1*.

Table 6.1: Summary of Contribution to Element 1: Choking the Release

Issues/Challenges	Contribution
• Significant Touch Time, >10% • Sequence dependent CCR • Potential CCR is located towards the front of production route: the first work centre • CCR is heavily shared • Parallel machine (production route)	• Using Buffer status (BS) as a reference to make work order release decision. • Utilise heuristic algorithm to allocate machine/mould resources to work orders, incorporating existing 'tacit knowledge' of company into the design. • Adopts detail work order scheduling (from Drum-Buffer-Rope) and sequencing.

Element 2: Managing the Priorities.

In S-DBR, greater emphasis is placed on execution stage than planning phase (section 3.3.2). To support decision making in execution stage, the concept of *Buffer management* (BM) is used. In execution stage, work order priority is determined through *Buffer Status* (BS). From the prior case companies reported, it is evident that failure to adhere by priority given by BS resulted in higher cycle time (Benavides and Landeghem, 2015). This failure includes not subordinating DD determination to status of operation. According to generic S&T for S-DBR, DD promised to customers is determined according to *Planned Load* (PL), as discussed in section 3.3.5.

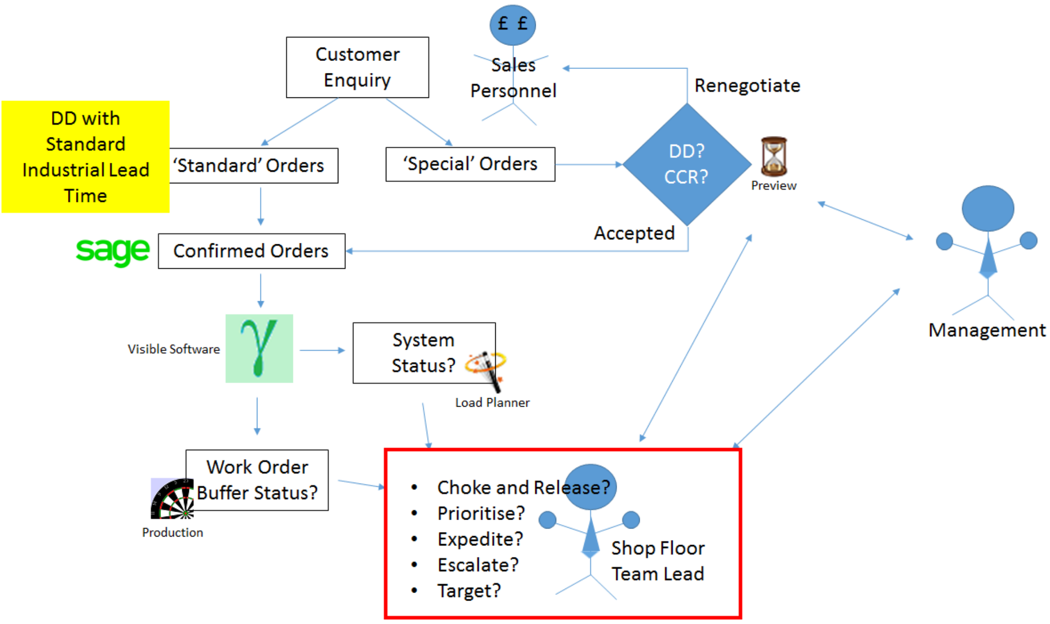


Figure 6.2: Interactions in Managing Priorities

In the case of Amberol, as the industry is familiar with the standard lead time offered, the management decides to maintain the existing practice. However, customer queries are categorised into *standard* or *special* as described in section 5.3.2 and 5.4.6. The process of DD determination incorporates both the *tacit knowledge* of Amberol and S-DBR concept. For general quotation, Amberol maintains the current standard delivery lead time offered to customers. Based on the confirmed orders, Visible can generate *warning* based on the *standard* system capacity threshold configured. PL and BS information are refreshed every 15 minutes, or every time work order progress order is updated and displayed (refer to section 5.3.4).

The availability of information through BS and PL, together with the use of *tacit knowledge*, helps team lead to determine if expedition options are available to *balance* work load on the shop floor to meet DD and keep overall work load within threshold. Decision making will be escalated to higher management if it is beyond the authority of shop floor team lead. This includes activating buffer capacities such as over time and additional shifts. *Figure 6.2* illustrates this interaction which highlights the use of Visible as both PPC and decision support tool in Amberol.

Unlike prior reported case companies, in addition to being underpinned by S-DBR, the PPC software developed for Amberol is integrated into the daily decision-making process of users. It effectively becomes a **decision support tool** to assist Amberol personnel to make informed decision, as discussed in section 5.3.3, 5.3.6 and 5.4.5. The summary of this research towards *Element 2* is shown in *Table 6.2*.

Table 6.2: Summary of Contribution to Element 2: Managing Priorities

Issues/Challenges	Contribution
• Lead time varies according to machine/mould combination. • Each product has different lead time. • Standard practice of adding ½ PB may not be practical for all cases. • Multilevel production structure/involves assembly	• Additional 5 days is added to the estimated completion date (total processing time + first available time slot on CCR) if the original estimated completion date falls in red zone and beyond. • Empower shop floor personnel to make decision based on information from Visible, 'tacit knowledge' and contextual environment. • Due date for all parts to be manufactured will have similar due date and assembly time as the part which takes longest time. • Assembly part which requires the longest post CCR processing time is used for all other assembly parts. This naturally aligns the priority of all moulded components to be available (*full kit*) without delaying assembly process.

Element 3: Dealing with CCRs

As highlighted in section 3.3.5, one of the important functions of dealing with CCR is to monitor its work load. In prior reported cases, potential CCRs are monitored either on a weekly basis or reactively. In contrast, potential CCRs in Amberol are monitored actively. This is due to the existence of wandering bottleneck between two potential CCRs.

As discussed in section 3.3.7, wandering bottleneck has been an issue in both DBR and WLC which employ bottleneck ruling. This is due to *pace* of the production system being dictated by *bottleneck*. Shift in *bottleneck* causes change in *pace* within the system. In S-DBR, as the *pace* is dictated by *market*, identification of potential CCRs and monitoring of their work load is to feedback system availability information to determine DD for new orders and BS for existing work orders.

Thus, in Amberol, the workload of potential CCRs (identified as machine and mould) are monitored on a daily basis (as discussed in section 5.3.3). The monitoring is embedded into Visible system and is part of the daily routine of shop floor team lead. Visible system repopulates resource utilisation periodically (five minutes interval), or during job progress update, which enables monitoring to be carried out as required. The purpose of monitoring is to provide early detection and quick intervention due to machine/mould combination which directly impact capacity of CCR.

Table 6.3: Summary of Contribution to Element 3: Dealing with CCRs

Issues/Challenges	Contribution
• Multiple potential CCRs • Wandering bottleneck	• S-DBR by nature is less susceptible to issues related to multiple CCRs due to the move of ‘drum’ from ‘CCR’ to ‘Market’.

Element 4: Load Control

Continue from the discussion in *Element 3*, other than using plan load monitoring to manage CCR (early detection and intervention to elevate CCR) and to deal with issue of *wandering bottleneck*, plan load is essential to determine safe due date. As discussed in section 3.3.5, this is done by adding one half of the production buffer (PB) to the first available time slot of the plan load. However, this is with the assumption where the position of CCR is in the middle of the process route. As demonstrated in prior cases where location of CCR is not in the middle of the processing route, Amberol adopted similar improvement concept proposed by Lee et al. (2010) to determine DD. However, due to significance of touch time in Amberol, additional adaptation is done to DD determination as discussed in *Element 2*.

The concept of plan load in LM is to enable CCR resources to be *pooled* without the need for detailed scheduling as in DBR (refer to section 3.3.5). In prior case companies where CCR capacity is affected by the sequence of certain product, additional group of rules have been introduced to avoid work load to appear to be underestimated. Through these rules, minimal preparation time is determined according to best order combination. However, the case report falls short of showing the details on how this is achieved.

In Amberol, the CCR resources are heavily shared resources. In addition, there is parallel machine routing problem due to different capacity of each machine. The machine capacity also changes according to the machine-mould combination. This causes complication in safe DD determination.

To overcome this complexity, *load balancing* is necessary through introduction of heuristic algorithm. Heuristic algorithm is developed to determine machine-mould best match based on *normal* situation (refer to section 5.3.2). As a result, a detailed schedule is proposed and populated by Visible system (refer to section 5.3.4). However, unlike the detailed sequencing rule in DBR where sequence must be strictly followed, shop floor team lead has the authority to make the final decision on whether to *accept* or *intervene*. This also avoids heuristic algorithm being perceived as *impractical* as the manufacturing environment is dynamic. Human intervention is allowed to further refine the *load balancing* performed by system. Other than utilising *tacit knowledge* to perform intervention on CCR loading, this intervention action is further assisted by the function of buffer management (BM): *prioritise*, *expedite*, *escalate*, or *target* (refer to section 3.3.4). This resulted in empowerment and culture change as discussed in section 5.4.5.

Although the concept of *Red Line* is introduced in the original S-DBR concept by Schragenheim and Dettmer (2001:175), it is not included in the generic S&T for S-DBR. However, in Amberol, as detailed in section 5.3.4, a *Red Line* is used as a reference to alert management if work order backlog at potential CCR approaches or exceed the ability to offer DD within standard delivery lead time. This forward looking (3 weeks ahead) feature allows shop floor personnel and management to react. *Time* is deployed as *buffer* to protect production against variation and uncertainties. The summary of contribution to Element 4: Load Control is shown in *Table 6.4*. To demonstrate the difference in contextual environment of this research and the contribution made through this research, *Table 6.5* compares this research with previous reported S-DBR implementation.

Table 6.4: Summary of Contribution to Element 4: Load Control

Issues/Challenges	Contribution
• Location of potential CCR is located at the front of production route, first work centre. • Although Visible is capable of providing safe due date, Amberol prefers to maintain its offering of existing standard delivery lead time.	• Additional 5 days is added to the estimated completion date (total processing time + first available time slot on CCR) if the original estimated completion date falls in red zone and beyond. • ‘Red Line’ (standard delivery lead time into the future) is utilised to alert Amberol on any work order backlog which will potentially jeopardise the standard delivery lead time offered. Intervention is introduced to keep work load below ‘Red Line’.

Table 6.5: Summary Table for Comparison between 6 Case Companies

Authors/Source	Benavides and Landeghem (2015) and Buestan (2015)				Hwang et al. (2011)	This research
	Company A	**Company B**	**Company C**	**Company D**	**Company E**	**Amberol**
General Characterisation						
Product	Plastic bags	Plastic bags	Medals	Offset printing	Furniture	Plastic products
No. of employees	75	130	40	105	5000	25
Production strategy	98%MTO, 2%MTS	90%MTO, 10%MTS	95%MTO, 5%MTS	100% MTO	MTO & MTS	100% MTO
Repetitiveness level	Almost all repetitive	Almost all repetitive	Almost all repetitive	At least 75% not repetitive	unknown	Non-repetitive. Refer to Section 4.2.1.2.
Order winners	Delivery	Quality	Delivery	Delivery and price	Delivery	Delivery and Quality
Product Characterisation						
Product structure	Single level	Single level	Single level	Single level	Multilevel	Multilevel
No. of families	4	4	3	15	unknown	Not applicable
Level of customisation	Standard components are combined	Standard components are combined	Standard components are combined	Customised	Standard components are combined	Semi-customised products
S-DBR Applicability/Assumptions						
Touch Time <10%	fit	fit	fit	fit	fit	Not fit, >10%
Number of CCRs	1	1	1	1	1	Possibly >1
Wandering bottleneck (potential CCR)	Stationary	Stationary	Stationary	Stationary	Stationary	Wandering between mould/machine
Sequence Independent at CCR	Moderately affect	Independent	Moderately Independent	Independent	Independent	Highly dependent
Location of CCR	Front	Middle	Front	Middle	Unknown	Front

Authors/Source	Benavides and Landeghem (2015) and Buestan (2015)				Hwang et al. (2011)	This research
	Company A	**Company B**	**Company C**	**Company D**	**Company E**	**Amberol**
S-DBR S&T Implementation Elements: ***Element 1: Choking the Release***						
5.111.1 Production Buffer (PB) to be 50% of original lead time	Implemented	Implemented	Not implemented	30%	Around 30%	PB is redesign. Refer to Section 4.2.2.
5.111.1 Different PB are created when difference between PB is larger than one quarter	One PB per family	Single PB	Single PB	One PB per family	Each factory chooses single PB according to the product which requires longest touch time.	Non-product/family dependent. Refer to Section 4.2.2.
5.11.3 Release schedule is effectively followed	95%	99%	95%	80%	Implemented	Not applicable. Refer to Section 4.3.4
Element 2: Managing the Priorities						
5.112.1 Current buffer status is available and visible to necessary departments	Supported by software with LCD display, coloured tags and integrated report among departments	Supported by software with LCD display and integrated report among departments	Supported by software with board display and integrated report among departments	Supported by software with LCD display and integrated report among departments	Management by sight. Supported by colour coded workshop job transfer zone. Work orders with Red or Black are manually recorded and displayed on black board.	Supported by software with computer LCD monitor display and integrated report among departments. Refer to Section 4.3.2.
5.112.2 BM is the only priority system	Additional sequencing rules subordinated to BM priorities	Fully implemented	Fully implemented	Additional sequencing rules subordinated to BM priorities	Fully implemented	Fully implemented with additional sequencing rules in the form of heuristic algorithm. Refer to Section 4.3.3 and 4.3.1.
5.112.2 Management does intervene BM priorities	Occasionally intervenes	No intervention	No intervention	Occasionally intervenes	No intervention	Intervene through discussion

Element 3: Dealing with CCR (Capacity Constrained Resources)						
4.11.3 CCRs are identified	Reactive approach to identify emerging CCRs based on buffer consumption	Formal procedure monitors workload resources weekly	Formal procedure monitors workload resources weekly	Reactive approach to identify emerging CCRs based on buffer consumption	unknown	Proactive approach in monitoring potential CCRs. Refer to Section 4.3.4.
4.11.3 Trial period before rolling out reliability offer	Not implemented	Not implemented	Not implemented	Not implemented	unknown	Not implemented
Element 4: Load Control						
5.114.1 DD (Due date) set according to first available slot on CCR plus ½ PB.	Full PB is added because CCR is located on the front end of routing	½ PB added as CCR is located in the middle of routing	Full PB is added because CCR is located on the front end of routing	½ PB added as CCR is located in the middle of routing	Unknown	Improvised DD setting mechanism. Refer to Section 4.2.2
5.114.1 DD is generated in less than 1 min	Fully implemented	Fully implemented	Fully implemented	Fully implemented	Unknown	Fully implemented. Potential CCRs are also identified. Refer to Section 4.3.4
5.114.1 Sales force is trained to call operations before committing to client	Fully implemented.	Fully implemented.	Fully implemented.	Sales force is not subordinated to operations	Unknown	Fully implemented. Refer to Section 4.4.6.
5.114.2 Not giving shorter delivery lead time (DLT) for free	Fully implemented. Orders with shorter DLT are charged	Fully implemented	Fully implemented. Orders with shorter DLT are charged	Partially implemented. Top management intervenes to offer orders shorter than DLT.	Unknown	Fully implemented. Shorter DLT are not selectively offered only for strategic purposes. Refer to Section 4.4.6.

Newly Added: **'Red Line' is used to provide early warning**						'Red Line' is used as reference to alert management as system loading approaches standard delivery lead time. Refer to Section 4.3.4.
Newly Added: **Frequent work order progress update on PL**						Authorised personnel utilises 'waiting time' in between 'machine cycle runs' to perform progress updates. Refer to Section 4.3.4.
Element 5: POOGI (Process of On-Going Improvement)						
4.11.5 Causes of non-trivial disruption (1/10 of PB delay) is reported and stored	Fully implemented	Fully implemented	Fully implemented	Fully implemented	Unknown	Function embedded in system awaiting to be fully implemented. Refer to Section 4.4.6.
4.11.5 Formal procedure is established to analyse causes of disruptions	Not implemented	Fully implemented	Partially implemented.	Not implemented	Unknown	Awaiting to be fully implemented. Refer to Section 4.4.6.
4.11.5 All corresponding causes for 'Red' are analysed	Not implemented	Not implemented	Not implemented	Not implemented	Unknown	Awaiting to be fully implemented. Refer to Section 4.4.6.

6.2.3 Development of Amberol's S-DBR S&T tree

Based on the discussion in section 6.2.2 and knowledge captured through AR (Action Research) cycles in Chapter 5, S-DBR S&T tree is developed for Amberol. This serves as a documentation to facilitate the Process of On-Going Improvement (POOGI) in Amberol. The generic and Amberol S-DBR S&T will be placed side by side to highlight the contribution of this research to the current S-DBR body of knowledge.

Table 6.6: S&T Comparison of Element 4.11.1 between Generic and Amberol

Element 4.11.1 Choking the Release		
	Generic S&T	**Amberol's S&T**
Need for Change	Having too many orders on the shop floor masks priorities, promotes local optima behavior and therefore prolongs the lead-time and significantly disrupts Due-Date-Performance (DDP).	Having too many or too little orders on the shop floor masks priorities, hides capacity of potential CCRs, promotes local optima behavior and therefore significantly reduces Throughput and disrupts Due-Date-Performance (DDP).
Strategy	The shop floor is populated ONLY with orders that have to be filled within a predefined horizon.	Remain Unchanged
Change Assumptions	• In traditionally run plants touch time is a very small fraction (<10%) of the lead time • Vast experience shows that, in traditionally run plants, restricting the release of materials, to be just half the current lead time before the corresponding due date, leads only to good results, and to not negative ramifications * (lead time reduces to less than half, DDP improves significantly, Throughput goes up and excess capacity is revealed). These results are achieved irrespective of whether a bottleneck exists or not. **Except for environments which are dominated by heavily dependent set-up matrixes. Those environments have to be dealt with in a different way.*	• In Amberol, touch time is >10%. • As the position of potential CCRs is located as the first work centre (gate) in the production routing, it automatically choke materials released into the system • Lead time is static. Thus, shortening lead time is not the primary objective. • As the 'market' is the ultimate constraint, the potential CCR has to be subordinated to the 'market'.
Tactic	• For each group of products currently having similar lead times, a buffer time is set to be equal to 50% of the current that lead-time. • Orders are released to the floor only a buffer time before their committed due-date - excessive Work-in-Process (WIP) is frozen until its time arrives according to the above rule. Warning: Do not use the shorter lead time as standard practice to get more sales	As the main objective is to fulfil orders within the standard industry accepted lead time (SILT), buffer time is set to be between 20% - 30% standard lead time. Subordination includes integrating 'tacit knowledge' of shop floor personnel into the decision making on machine-mould combination.
Warning	Trying to be more accurate than the noise is useless, distracting, and definitely delays results.	• Trying to be more accurate than the noise is useless, distracting, and definitely delays results. • Focusing on reducing lead time equals increasing machine cycles. Using this as performance measurement will introduce local optima. In addition, it will introduce undesired/distorted human behaviour.

Table 6.7: S&T Comparison of Element 5.111.1 between Generic and Amberol

Element 5.111.1 Set Production Time Buffers		
	Generic S&T	**Amberol's S&T**
Need for Change	• Having a production time buffer which is too short or too long, results in chaos and jeopardizes DDP. • If the buffer is too short, there is not enough time and expediting increases. • If the buffer is too long, there is too much WIP, priorities are masked and the lead time is unnecessarily increased. • Applying a unique buffer for each product having a different production lead time may result in too many buffers, bringing about complexity for no reason. • Applying a single buffer for products having considerably different lead times creates chaos.	Remain Unchanged with the following addition: The original Amberol production allocated individual buffer time to each work centre. This caused available resource capacity to be masked. In addition, 'time' is wasted and not able to be used to provide protection at other work centres particularly those located towards the end of the production route. This is in part due to 'touch time' is significant.
Strategy	The Company has appropriate size production time buffer(s).	Remain Unchanged
Change Assumptions	• When setting the buffer, trying to be more accurate than the noise does not help, but rather can cause damage (a fundamental concept of TQM). In the extremes - when the buffer is much too short or much too long - there is chaos. • Between these two extremes there is a large plateau. • In traditionally run plants, work is released much ahead of the due date (the second extreme) to the extent that there is too much inventory and priorities are masked. • Therefore, in traditionally run plants, cutting the current production lead time by 50% will safely move the system away from one extreme without the danger of reaching the other extreme. (See U-Curve Hyperlink) • When there are processes with significant* static** lead times (such as heat treatment, some outsourced production processes, etc.), this lead time should not be cut into half when determining the buffer.	Remain Unchanged

	Note: Transportation times should not be considered when determining production time buffers More than one production buffer is set ONLY in cases in which the resulting production buffers are significantly* different. ---- • * Significant means more than one quarter of the buffer. • ** Static processes means operations that cannot be shortened.	
Tactic	• Production Time buffers are set to be equal to 50% of the existing production lead times. • Significant static lead times are handled properly. • Different production buffers are created ONLY when the difference between production buffers is larger than one quarter.	• Production Time buffers are set to be the SILT. • Under circumstances where expected due date falls within 20% of existing SILT, an additional 30% SILT is added to the expected finished date.
Warning		

Table 6.8: S&T Comparison of Element 5.111.2 between Generic and Amberol

Element 5.111.2 Generating Release Schedule		
	Generic S&T	**Amberol's S&T**
Need for Change	• When the Bill Of Material (BOM) for a product consists of more than a few part numbers and levels, it is quite cumbersome to manually determine what, how much and when to release according to the set buffer(s). • Conventional MRP/ERP systems provide the required "netting" capabilities. • However, since they calculate the timing of releases according to deterministic time information in the routings and the BOM, the times they set for release of materials conflict with the need to release materials according to the set buffer(s).	Remain Unchanged

Strategy	The release of work is scheduled in accordance with the set buffer(s).	Remain Unchanged
Change Assumptions	• Most commercial MRP/ERP systems can be configured to support release of all work in accordance with the agreed time buffer(s) • Also, commercial S-DBR/BM software are available which utilize the data in a Company's existing MRP/ERP system to schedule the release of all work for an order in accordance with set buffer(s). • The Inputs from the existing system required by for these software to operate are: 1. Open orders (as well as the products included in each order) quantities and due dates Bills of material Inventories at all levels (if the company differentiates inventory at different steps in the routing, this WIP must be included) 2. Batching information (rules, & data) 3. In cases where the due date to the client is the delivery date, the transportation times to the required destination (release date is determined by due date minus transportation lead time minus buffer) • Cutting the buffer times in half (according to Step 5.111.1) ensures reducing both lead times and WIP inventories by one half. • Any attempt to "improve" by releasing various parts needed for the same assembly at different times, does not significantly contribute to the overall reduction in lead-times and inventories, but dramatically increases complexity, and as a result significantly exposes the company to missed due dates and hassle. • Any attempt to use this step to also clean the data leads to major delays in the implementation without contributing much to the magnitude of the results. In particular, the data base should be left as-is since many data elements are currently used for other proposes (like financial reporting). • The same applies to batching rules; they should be left intact. • If there is a flaw in the data, or the batching rules, which does impact results, it will be flagged once the flow is corrected - see step 4.11.3 and 4.11.5.	• The existing ERP system with its bespoke manufacturing module releases jobs immediately into the production system. • Existing BOM information in ERP is incomplete. Updating it requires 3rd party developer to change the data structure of the ERP system. In addition, it will require revamp on how BOMs are coded. (Existing BOM does not include the break-down of necessary moulded components). This takes time and might cause chaos and unsettle non-manufacturing personnel. • Visible (the bespoke S-DBR based PPC software) maintains the break-down moulded components of assembly product, mould resources, and process time related information. As one single product may require more than ten moulded parts, given that the touch time is significant, inaccurate BOM (on moulded components) will not reflect actual system loading. This will cause unrealistic DD to be quoted, resulting Visible to be viewed as impractical by the shop floor. • Visible obtain work order related information from ERP system. This includes: customer name, product, quantity, order date and delivery date. • To ensure all moulded components are available (full kit) when the part with the longest 'moulding' time is ready to be assembled, the longest finishing/assembly time required by a moulded component within the assembly is used for all components. This avoids the need to have 'assembly buffer'. • As the potential CCR is a heavily shared resource with additional complexity due to parallel machine routing options, choice of route affects the capacity of the resource selected. Warning: The more complex an environment is, all the more the solution should be simpler.

	• A release schedule (permission to work) of common parts at the divergent points of the flow should also be provided, otherwise these common parts may be diverted to the wrong process/products. Warning: The process times within MRP routings are also used for other purposes such as calculating standard costs etc.	
Tactic	• The company assigns person(s) familiar with the company's existing system to either configure the system to support the release of work according to agreed time buffer(s) or write the interfaces for a commercial S-DBR/BM system. • Warning: do not change anything in the current system other than extracting the required inputs as the data may be needed for other purposes (e.g. Although routing times are not needed to determine the release of work, they are needed for cost considerations). • The company implements a computerized S-DBR/BM system that properly generates release schedules for all entry and diversion points in the production process according to the set buffers.	• The release schedule is generated based on the following considerations. The heavily shared resources have been strategically grouped to reflect the 'tacit knowledge' of shop floor personnel under 'normal' circumstances. This information is integrated with the 'best' machine-mould combination under 'normal circumstances'. The above information is built into a heuristic algorithm which reflects the 'tacit knowledge' used by shop floor personnel under 'normal circumstances'. • Release schedule refreshes according to latest confirmed order, system loading, and work order progress. • The schedule generated is to provide additional information for shop floor personnel to support their decision making.
Warning		

Table 6.9: S&T Comparison of Element 5.111.3 between Generic and Amberol

Element 5.111.3 Obeying the Release Schedule		
	Generic S&T	**Amberol's S&T**
Need for Change	• Local Efficiency is a prevalent mentality and behavior in conventionally run plants. • Following the release schedule brings (in most environments) the resources participating in the production process to become partially idle (especially those at the beginning of the process during the initial stage of implementation when the excess work-in-process is flushed out). • Therefore, the mentality of local efficiency might create pressure on the starved resources to break the schedule and release material too early.	Remain Unchanged
Strategy	The release schedule is effectively followed and complied with	Remain Unchanged
Change Assumptions	• When the material management people follow the release schedule, results are achieved very quickly. • After as little as one production lead time, LT shrinks to less than half, WIP reduces, and in most environments, DDP increases dramatically. • When people at the plant understand that starvation is expected temporarily and from time to time, they are willing to tolerate the lack of work for awhile (enough for the results to appear and the work to pick up). • Sometimes, technical aspects of production necessitate batching.	• When shop floor personnel is aligned to release schedule, results are achieved very quickly. • Hidden capacity is exposed, number of shift is halved during peak season. • Shop floor personnel understands the importance of team work. Performance is not measured by highest number of machine cycle, but the alignment of capacity usage according to work order priority.
Tactic	• An explanation is given to the operations personnel on the expected effect of the release schedule on their work. • Unless technical requirements necessitate an exception, orders are released strictly according to the established schedule (nothing is released ahead of the schedule)	• Shop floor team lead is encouraged to utilise both tacit knowledge and release schedule to make final release decision.
Warning		Visible is a decision support tool. Using it to dictate shop floor personnel will result in undesired behaviour.

Table 6.10: S&T Comparison of Element 5.111.4 between Generic and Amberol

Element 5.111.4 Excessive WIP		
	Generic S&T	Amberol's S&T
Need for Change	When there is excessive WIP on the production floor (prevalent in make to stock environments driven by efficiency), priorities may continue to be masked for quite some time even after the release of work is choked.	Not Applicable
Strategy	The shop floor works ONLY on orders that have to be filled within a predefined horizon.	Not Applicable
Change Assumptions	Excessive WIP that should be frozen includes all orders already released to the shop floor for which the time to their due date is longer than the buffer length plus 1/3. (less than that would be optimizing within the noise).	Not Applicable
Tactic	Excessive WIP orders are frozen until their release date.	Not Applicable
Warning		

Table 6.11: S&T Comparison of Element 4.11.2 between Generic and Amberol

Element 4.11.2 Managing the Priorities		
	Generic S&T	**Amberol's S&T**
Need for Change	• Hectic priorities (hot, red-hot and do-it-NOW) cause chaos on the floor. • Even when material release is properly choked, not having a priority system can cause some orders to still be late.	Remain Unchanged
Strategy	The shop floor is governed by a simple, yet robust, priority system.	Remain Unchanged
Change Assumptions	• Vast experience has shown that when work is released according to set time buffers, excellent results are obtained by using a simple priority system that is based solely on the time lapsed since the release. • Buffer Management (BM) is setting priorities only according to the degree the buffer-time is consumed (four color code system - green: less than one third of the buffer time passed is lowest priority and black: more than the time buffer passed is the highest).	Remain Unchanged
Tactic	Buffer Management (BM) is the ONLY priority system used on the shop floor.	Remain Unchanged
Warning		

Table 6.12: S&T Comparison of Element 5.112.1 between Generic and Amberol

Element 5.112.1 Setting Production BM System		
	Generic S&T	**Amberol's S&T**
Need for Change	• If the priorities are not current, available & visible to production managers and workers, working on the right priority is left to chance. • The priority of orders a department has to work on may change frequently. • Murphy causes the priority of some orders to change unexpectedly.	Remain Unchanged
Strategy	The current buffer status is available and visible to anyone with the need to know the status.	Remain Unchanged
Change Assumptions	• S-DBR/BM software packages provide the buffer status of all work orders according to their buffer consumption. • It is relatively easy to modify commercial ERP/MRP systems to calculate and display buffer status on production work order lists. • To provide the production floor with updated priorities, the following information must be known: 1. The buffer status of all work orders according to their buffer consumption (provided via modified ERP/MRP or S-DBR/BM software package) 2. The completion status and location of every work order - the steps already completed and current step the order is waiting to be or actually being processed (provided via routing and updates in company's ERP or MRP system) • To keep priorities current per department, information on completion of work in every department is needed. • Understanding the benefits of having a robust priority system would diminish resistance of departments to report work completion. • In cases of scrap, the modified ERP/MRP or 3rd party S-DBR/BM system adjusts the priority of corresponding work upstream. • The foreman knows best how to ensure his department follows the given priorities.	Remain Unchanged

	• The recommended way to make priorities visible on the floor is to frequently provide the foreman with the priorities list of the work at his department. Note: When work spends non-negligible time in a work station, it makes sense to mark the color status on the physical WIP. The safest and most accurate way to make priorities visible is to have screens, which are being updated on-line, showing the buffer status of orders at each department.	
Tactic	• Existing ERP/MRP system is modified to show buffer status or proper interfaces are programmed between a 3rd party S-DBR/BM system and the Company's existing ERP/MRP system to show buffer status on work order list. • The company sets the mechanism to have reports of work transitioning from one department to another. • The company sets the mechanism to provide foremen with updated list of the orders buffer status at their department. • If needed, buffer color tags are placed on the physical WIP, and/or screens are set at each department to show the orders buffer status.	• Buffer status is shown on Visible software. • Work Order status display is customised according to department (both manufacturing and non-manufacturing). • As touch time is significant, daily work order progress update is required. It is updated by the quantity completed. • A 'memo' functionality provides a common communication platform to capture 'information' relevant to every work order from authorised users (from every department). This is particularly useful to bridge the communication gap between manufacturing and non-manufacturing. For example, status of an ordered special component or credit clearance status of customer.
Warning		

Table 6.13: S&T Comparison of Element 5.112.2 between Generic and Amberol

Element 5.112.2 Following Production BM System		
	Generic S&T	**Amberol's S&T**
Need for Change	An environment used to operating with hectic priorities is not transforming overnight to operate according to a single robust priority system.	Remain Unchanged
Strategy	The right priorities are being followed.	Remain Unchanged
Change Assumptions	The buffer management rules are easy to understand and agree on: • Red gets a higher priority than Yellow. • Yellow gets a higher priority than Green. Workers should not be allowed to process a Yellow order before a Red order or a Yellow order before a Green order. Orders with the same color get the same priority. Between same color priorities, the foreman should determine which order to process first based on local considerations to maximize flow. Trying to provide sub priorities within a given color assumes one can be more accurate than the noise and may violate flow considerations. Vast experience shows that sub priorities do not contribute to better results but to the opposite. Note: When orders from different production buffers are waiting for the same resource, using only the buffer colors to set priorities may lead to deterioration in the DDP. In these cases, using the Due-Date as a secondary priority prevents the deterioration from occurring. Reporting is not always accurate, but due to the priority system, most inaccuracies can be spotted and corrected the same day. In some cases, the report of work completed would not be updated in the system, resulting in work with a high priority color which is not located where the system indicates it is. In some cases, the quantity of work processed would not be accurately provided to the system resulting in "orphans"- work with no color. When workers understand that following the buffer priorities would bring stability to the floor, they are motivated to follow the priorities. In traditionally run plants, Management is often changing priorities on the floor (for example, to ensure a shipment to a client is sent on time). With proper education and coaching, Management could be trained to refrain from interfering in priorities setting.	Remain Unchanged with the following addition: Green gets higher priority than Blue. Shop floor uses BM as a guide to make decision on which work order to be processed. As 'touch time' is significant and production is 'sequence dependent', authorised shop floor personnel is encouraged and empowered to use 'tacit knowledge' to make informed order release decision according to contextual environment.
Tactic	• Production managers are trained to follow and enforce the BM priorities.	Rush orders are accepted based on 'Preview' module in Visible and

	• Periodically, the plant manager verifies that priorities are followed, sampling the work processed by and the queues in front of workstations. • Workers are trained to follow the priority system. • Foremen are trained on the benefits of timely reporting of: 1. Work completion, Missing high priority work, Work with no colour (orphans) 2. Scrap Management is trained and coached in not intervening and violating the priorities.	discussion with shop floor personnel on feasibility. The due date delivery of the order will automatically place the work order in 'Red'. Management is able to discuss with shop floor personnel on possibility to change priority of certain orders. Visible can be used to 'simulate' and show the 'systemic effect' of the 'local action' taken. Shop floor team lead empowerment is achieved through the integration of BM functions: prioritise, expedite, escalate, and target, into the daily decision making process.
Warning		BM is a signalling tool. Together with its functions, is used as a decision support tool. Using it to 'dictate' and 'disregard' shop floor risk introducing undesired human behaviour.

Table 6.14: S&T Comparison of Element 4.11.3 between Generic and Amberol

Element 4.11.3 Dealing with Capacity Constraint Resources		
	Generic S&T	**Amberol's S&T**
Need for Change	In many plants, there are Capacity Constraint Resources (CCRs) that prevent the attainment of the needed DDP.	Remain Unchanged
Strategy	Remarkable DDP is not jeopardized by the emergence of Capacity Constraint Resources (CCRs).	Remain Unchanged
Change Assumptions	If a CCR exists, work-in-process piles up in front of it. When material release is restricted, the only work centres that have work-in-process continuously piling up in front of them are the CCRs.	Remain Unchanged with the following addition: CCR is non-static, could be machine or mould. However, they are both located at the front of the production route.

	In most cases, additional capacity can be exposed by simple means like: • Ensuring that CCRs do not take lunch or shift-change breaks, • Offloading work from the CCRs to less "effective" work centres that have ample excess capacity, • Using TPS/LEAN techniques to shrink the set-up time on the CCRs, • Using 6Sigma techniques to identify major causes of downtime and to reduce process cycle time variation. • Giving overtime approval for the CCRs, etc. Whether the production buffer is very short (e.g. 8 weeks), 1 month is a reasonable amount of time to identify the consistency of Due-Date-Performance (DDP).	Due to non-static characteristic of the CCRs, the cascading effect of work orders create confusion in following the signalling mechanism in BM. For example, a product, Machine is not a CCR, but mould is. Work order (WO1) which has Buffer Status (BS) in Blue has to be released 'immediately'. Else, due to the mould being the CCR, the BS of queued work order (WO9) is Red. The decision made in 'machine-mould' combination will directly affect machine capacity. This has implication to overall system throughput and DDP. 'Machine-mould' decision has to be made collectively based on 'tacit knowledge' and 'on the ground' situation. Visible, as a decision support tool will provide both raw and analysed information to facilitate decision making. CCRs have to be 'subordinated' to 'market'. To achieve this, there are options which are within the authority of shop floor team lead (Expedite). Options beyond authority will need to be discussed and obtain approval from higher management (Escalate).
Tactic	• CCRs are identified and capacity is effectively elevated. Notes: • When the required DDP is sustained for 1 month, the green light is given to sales for mass roll-out of the reliability offer. • To ensure CCRs do not disrupt DDP, it is essential to move rapidly to implement 'Load Control' (Step 4.11.5).	• CCRs are identified and subordinated. • An additional column is used to represent the BS of the work order at the end of the queue. This makes BS of both machine and mould practically visible to user to make decision, avoiding confusion. • Moulds which has associated work order with BS in Red and beyond is flagged up to alert management.
Warning		

Table 6.15: S&T Comparison of Element 4.11.4 between Generic and Amberol

Element 4.11.4 Load Control		
	Generic S&T	**Amberol's S&T**
Need for Change	• Choking the release of work and following correct priorities system improve flow, shorten the lead times and reveal ample capacity. • Considering the load of the system when releasing orders can improve DDP even further. • Offering "quoted standard lead times" cannot continuously coexist with high due-date performance when sales are going up. (Because: When sales are growing fast the load on key resources increases. • The mismatch between dates which are based on standard LT and actual deliveries is unavoidable.)	Remain Unchanged
Strategy	The delivery due dates the Company is quoting to customers are always met, irrespective of the growth in sales.	Remain Unchanged
Change Assumptions	• It is relatively easy to meet all due-dates when the commitments are given based on actual loads and S-DBR and BM are in place. • Within minutes a date can be given based on load already committed rather than standard lead time.	Remain Unchanged with the following addition: Forward looking planned load offer 'buffer time' for management to introduce intervention (activate buffer capacity) to commit delivery within SILT. Adequate scheduling is able to provide essential information on work order progress and resource utilisation for decision making. Due to parallel machine scenario with each machine possessing different production capacity, a mechanism (as in Tactic) derived from shop floor's 'tacit knowledge' is develop and embedded within Visible. Choice in machine-mould combination affects the capacity of machine resource. Machine capacity affects choice in machine-mould combination. While certain machine resource collectively represents a pool of common resource to certain products, individual machine is also unique resource to certain products.

Tactic	The mechanism is in place to enable sales to determine and quote, within minutes, reliable due-date commitments which are based on actual load (on CCRs).	Remain Unchanged with the following addition: Red Line, Load Balance and Work Order Progress Update is part of effort to subordinate CCR to market. **Red Line** A 'Red Line' is added to Planned Load display. 'Red Line' is drawn according to the SILT from 'today'. This provides a simple indication on system loading with respect to SILT. Shop floor is empowered to utilise 'tacit knowledge' and authorised buffer capacity to keep system loading within 'Red Line'. This includes violating conventional 'machine-mould' combination using 'tacit knowledge'. If the 'Red Line' is exceeded only for a particular resource, intervention such as over-time can be introduced only for the necessary resources. Shift is introduced if necessary. As shifts requires time for management to employ additional shop floor personnel, early warning from 'Red Line' provides management the necessary time to plan resources ahead of time. **Load Balance** A heuristic algorithm is developed to mimic basic decision making under 'normal' circumstances. Loading on machine resources are 'balanced' using the heuristic algorithm above. Work Order **Progress Update** Visible provides interface to update work order (WO) progress. This includes WO machine assignment (occupy resource), units

		completed (if partially finished by the end of a day), or completed (release resource).
Warning	When answering a new challenge it behooves doing it in a way that minimizes the change to the already established practice.	Remain Unchanged with the following additions: Both Red Line and Load balance algorithm are tools to process raw data and output in a form to facilitate shop floor personnel to make informed decisions based on contextual environment and 'tacit knowledge'.

Table 6.16: S&T Comparison of Element 5.114.1 between Generic and Amberol

Element 5.114.1 Setting Order Due Date		
	Generic S&T	**Amberol's S&T**
Need for Change	• As sales are growing, the irregular way in which orders are coming wastes capacity to the extent that DDP are in danger. • When sales grow substantially, permanent CCRs appear. • If sales continue to commit to due-dates according to fixed lead time, the chances to meet due-dates diminishes.	Remain Unchanged
Strategy	Due-dates given by the sales force are always met.	Remain Unchanged
Change Assumptions	• In a well-run plant, most of the time an order spends on the floor it is waiting to be processed by the CCR. • Therefore, when the CCR is performing on the order in (about) the middle of the order's buffer the chance to meet the DD is very high. Note: The actions taken in "dealing with CCR step" may rapidly elevate a CCR's capacity to the extent that another resource should be considered as the CCR.	Remain unchanged except with the following addition: The potential CCRs are located towards the front of the production route.

Tactic	• Due-date commitments are given according to first available slot on the CCR plus ½ the production buffer. (See Hyperlink) • The sales force is trained to call operations before giving the commitment to client. • Operations is organized to give the answer in less than a minute.	• Due-date commitments are given according to first available slot on the CCR plus full production buffer. • Occasionally, to cope with market demand over peak season, DD which is longer than SILT has to be given or re-negotiate to deliver in batches. • For 'large orders' (typically above 50 units), which constitutes less than 5% of the total orders, the DD is determined by using 'Preview' module in Visible. • Through 'Preview' module, if system loading is not able to commit to SILT, it will propose new DD by adding 5 days to the (processing time + first available time slot on CCR).
Warning		

Table 6.17: S&T Comparison of Element 5.114.2 between Generic and Amberol

Element 5.114.2 Not Wasting RR (Rapid Response) Opportunities		
	Generic S&T	**Amberol's S&T**
Need for Change	• Giving due-dates based on load may result in short lead times. • Giving something for free jeopardizes the ability to charge for it.	Remain Unchanged
Strategy	The Company does not waste the opportunity to command high premiums for shorter lead times	Remain Unchanged
Change Assumptions	The way to achieve all the following requirements: • Synchronize due-date commitments with available capacity on the CCR. • Not give (for free) commitments which have shorter lead time than the standard lead time. • Use one mechanism for scheduling and controlling the shop floor, …is to increase the order buffer by the right amount (see Tactic).	Remain Unchanged

	Note: Having an order buffer may result in completing orders ahead of time. Keeping FG (Finished Goods) inventory is costly, quite often clients may appreciate receiving orders ahead of time.	
Tactic	The due-date is committed to be equal to present date plus the further between 1) standard lead time and 2) first available slot on CCR plus ½ of the production buffer. In cases that the commitment was given according to standard lead time, the time buffer of the order is increased by the difference between 1 and 2 above. Orders continue to be released just (their respective) buffer time before their respective due date. (See Hyperlink) Since FG inventory may be created due to the above action when the load is relatively low, salespeople would offer the clients the option of receiving the shipment early. The possibility (without commitment) of receiving the shipment ahead of time can also be used when presenting the Reliability service - it would strengthen the offer. Note: When the order buffer is much longer than the production buffer, and clients are not willing to accept the delivery early, the company should consider whether to apply load control.	DD committed to be equal to present date plus the further between 1) SILT 2) First available slot on CCR plus full production buffer For 'large orders' (typically above 50 units), if estimated completion date falls in Red Zone or beyond, additional 5 working days is added to it. Allowing customers to receive delivery ahead of promised SILT improves Amberol's image. If a delivery is not to be shipped earlier than SILT, it will be held temporarily in FG area.
Warning		

Table 6.18: S&T Comparison of Element 4.11.5 between Generic and Amberol

Element 4.11.5 POOGI Systemically Improving Flow		
	Generic S&T	**Amberol's S&T**
Need for Change	When the source of disruption affects several work centers, accumulation of WIP cannot be used as an effective guide to the source of the disruption.	Remain Unchanged
Strategy	Major sources for disruptions are identified and prudently dealt with.	Remain Unchanged
Change Assumptions	Definitions: A disruption is a delay in the flow. • Per each work order, delays accumulate. • A non-trivial disruption is defined as one that causes a delay longer than one tenth of the production buffer time.	Remain Unchanged

	• A disruption that endangers on-time delivery is a disruption that causes an order to reach the red zone. • A major source of disruptions is a source that systematically creates disruptions that endanger on-time delivery. • Most non-trivial disruptions are not, and do not contribute to, disruptions that endanger on-time delivery. • Often, orders reach the red zone because of non-trivial disruptions that occurred while the order was still in the green and/or yellow zones.	
Tactic	• The company implements a Process of OnGoing Improvement (POOGI) by: Ensuring the cause for each non-trivial disruption (each 1/10 of production buffer time delay) is reported and stored in the general bank of disruptions. • A cause for a disruption is the answer to the question, "What is the work order waiting for?" When the color of a work order is red, all corresponding disruptions to that work order are pulled from the general bank and are placed in the bank of disruptions that endanger on-time delivery. • Once a period (e.g. weekly), a Pareto analysis on the relevant bank provides the data needed to pinpoint the major sources of disruptions that endanger on-time delivery. • Cross functional improvement teams are guided to take prudent actions to eliminate the major sources of disruptions that endanger on-time delivery.	Remain Unchanged except with the following additions: As it is a small company with 25 employees, any disruption is immediately made known to shop floor team lead. Disruption is collectively solved at shop floor level and report to senior management. Senior management will be involved if proposed solution falls beyond the authority of shop floor personnel.
Warning		Measurement and the reward and penalty which comes with it has to be applied with care. Inappropriate measurement and consequences will result in undesired and distorted human behaviour.

6.3 Signalling Mechanism in PPC

Signalling mechanism is essential in PPC for MTO environment. This is evident in the two PPC solutions discussed in this document: WLC and S-DBR. As reviewed in section 3.4, although both WLC and S-DBR originated from different philosophical perspectives, they present similarities under certain assumptions. This resonances with WLC researchers to encourage *cross breed* research where both WLC and S-DBR could mutually benefit from each solution's salient features.

Drawing from the discussion in section 6.2.1, *Figure 6.3* below positions TOC based MTO PPCs (OPT, DBR, and S-DBR) and WLC on a continuum of *Planning and Execution*. On the far right is *high planning* and *low execution* and on the far left is *low planning* and *high execution*. S-DBR, due to its simple mechanism in planning stage by referring to the PL of potential CCR, it is proposed to be placed on the far left on the continuum. WLC is proposed to be placed on the other end of this continuum. This is due to its emphasis on heavy planning by monitoring all work centres.

The solution developed for Amberol requires additional *planning* through *detailed scheduling* and *heuristic algorithm*. However, in execution, it maintains the concept of *high execution* of original *S-DBR*, allowing shop floor personnel to make final decision according to *tacit knowledge* and *contextual environment*. In planning stage, the concept of PL plays an essential role. BM provides a simple signalling system in execution stage. As demonstrated in section 6.2.1: *Managing Priorities*, the functions embedded in BM signalling system assist management in making informed decisions. The BS represented by colour code (Red, Yellow and Green) provides visual and simple guide for shop floor personnel to take reference in decision making process.

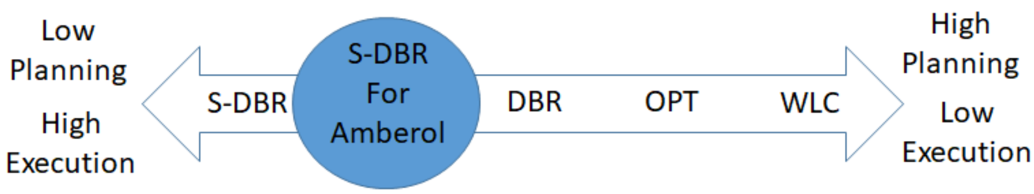


Figure 6.3: Position of S-DBR and WLC on a Planning and Execution Continuum

As discussed in section 3.4.1, WLC researchers has called for a paradigm shift in PPC. This involves the integration of two independent decisions levels: due date and release date settings, into an integral due date setting procedure. The effectiveness was demonstrated using simulation. The use of BM as the signalling mechanism, as demonstrated in this research can potentially be used to realise the paradigm shift in WLC. By using BM and PL, both due dates and planned release dates are set together according to the availability of the PL. In addition to integrating the two decision levels into one, BM together with its BS and functions translates the two decision levels into an effective shop floor priority dispatch mechanism. *Figure 6.4* illustrates how BM and PL can be can be of relevance to WLC.

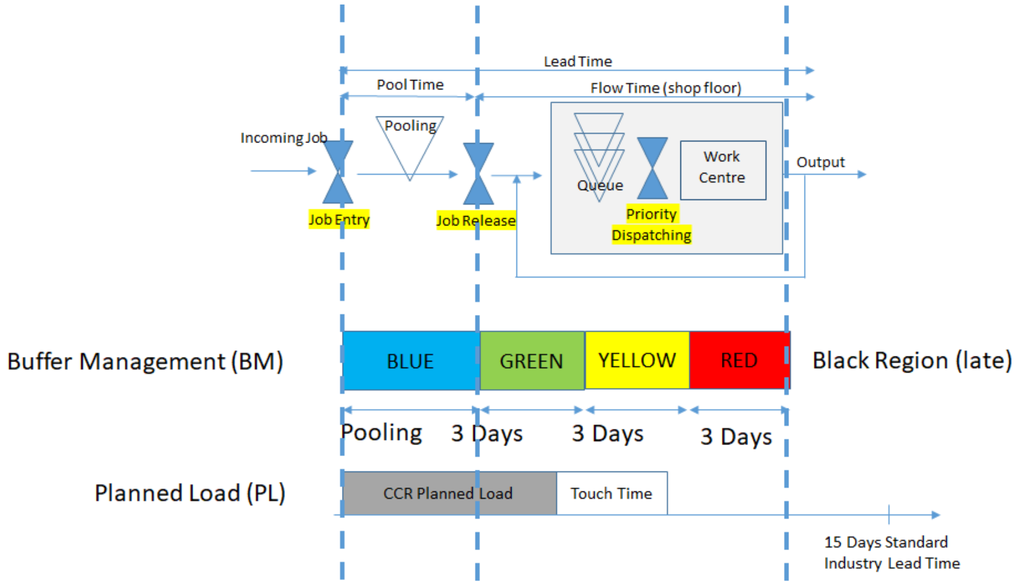


Figure 6.4: Utilising BM and PL in WLC

6.3.1 Reflecting on a Practitioner Led WLC Implementation

This section attempts to further demonstrate the potential of applying BM in WLC. BM lens is used to analyse a reported WLC case, to be known as Company W in this section. The case selected is a practitioner-led WLC implementation with limited researcher intervention reported by Silva et al. (2015). This WLC case presents similarity to the implementation discussed in this document where both are practitioner led. The areas where WLC has been adapted to suit contextual requirement of the case is highlighted and reviewed using the concept of BM and its four functionalities: *prioritise*, *expedite*, *escalate*, and *target*.

Customer Enquiry Stage

In Company W, the DD is determined through forward scheduling. This includes the consideration of pool delay (PD), necessary time to complete all work order accepted at extrusion capacity group (expected queue time at first process) (FQ) and the 'fixed time' for each operation in the routing (FT), represented by *Equation 6.1* below.

$$DD = PD + FQ + FT \qquad (6.1)$$

With the assumption that there is constant availability of raw materials, no material lead time is included. Other than the queue time at first process, it has ignored expected queueing time at subsequent processes. However, the necessary processing time (fixed) for every required process in the routing is considered. As highlighted by Silva et al. (2015), this is a simplified approach due to the contextual environment.

From the perspective of S-DBR, this is a practice of 'simple' or 'low planning' which resembles S-DBR. The case company has identified the first process being the potential CCR. Thus, it has to take all accepted workload in this process into consideration. The remainder of processes are assumed to be operating with 'road runner' attitude. In addition, the position of potential CCR is towards the front of the routing process. Comparing *Equation 6.1* with *Equation 4.2* in section 4.2.2, it is seen that the *FQ* is similar to the '*First available time slot at Potential CCR*'. The '*FT*' is equivalent to the necessary touch time.

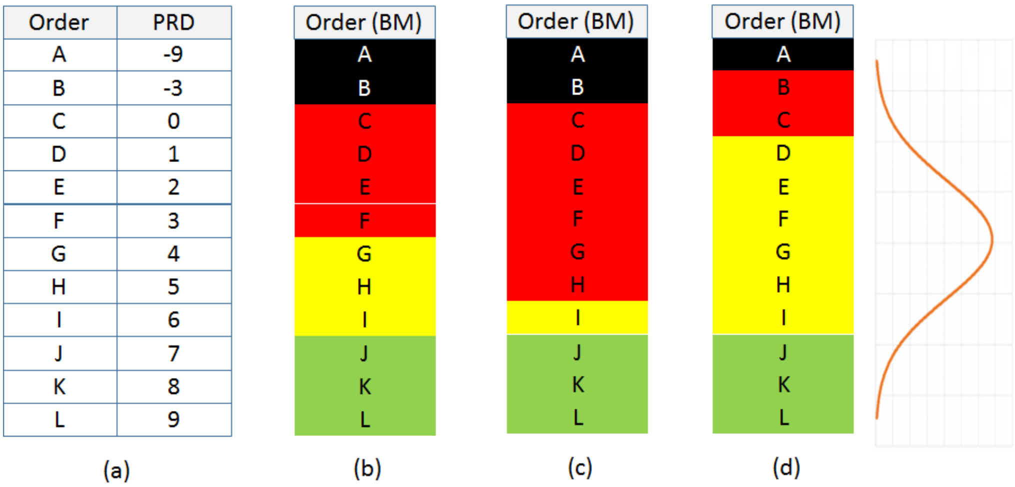
Order Release Decision Making and Priority Dispatching

For each work centre, minimum and maximum workload norm is set. The purpose of minimum workload norm in this case is to avoid starvation. Due to the contextual environment, productivity reduction is monitored by the company and is triggered if the workload falls below a predetermined threshold. In the determination of maximum workload, contextual factors such as size of product to be manufactured and storage space in between work centres are taken into consideration.

Order Completion Date (OCD) and Planned Release Date (PRD) of each order at each work centre is determined through backward scheduling from the DD. Urgency of work orders are determined by sorting PRD. Other than PRD, release decision is also made according to contextual consideration such as setup and batching consideration.

As acknowledged by Silva et al. (2015), this is not a simple FIFO (First-In-First-Out) sequence often adopted in WLC simulation.

From the perspective of S-DBR, this is an evidence of *High Execution*. In addition, capacity at work centres is allowed to be temporarily adjusted to expedite processing of work orders if necessary. To avoid *cherry picking*, the list of queueing work orders at each work centre is reduced. BM can produce a simple signalling mechanism which facilitates ‘High Execution’. It is proposed that the simple visual representation of prioritisation is more effective than numerical representation.



Order	PRD
A	-9
B	-3
C	0
D	1
E	2
F	3
G	4
H	5
I	6
J	7
K	8
L	9

Figure 6.5: Comparison between PRD and BM Representation

With reference to *Figure 6.5*, example of work order representation using PRD and BM is shown in *Figure 6.5 (a) and (b)* respectively. With reference to *Figure 6.5 (b)*, BM provides simple and visual representation to prioritise work orders: *Prioritise*. Orders released from pool and at each work centre is controlled using BM. *Blue* zone can be created to represent *Pooling* zone where orders are not supposed to be released. It is desired for majority of work orders to be released in *Yellow* zone. This could provide an easy mechanism to *label* urgent or rush orders. By placing a sooner delivery date, it will automatically appear in *Red* zone, which will be *expedited*.

BM is also able to provide monitoring and avoid *cherry picking* behaviour. As work orders are to be processed according to priority indicated by the colour any early release can be easily spotted and triggers further inquiries. This avoids the need to adjust queuing size before work centres.

In addition to the function of monitoring, BM facilitates shop floor personnel in making decision on which work orders to be expedited: *Expedite*. Through its systemic signalling mechanism, BM could provide early warning on potential delays. Referring to *Figure 6.5 (c)*, it shows a growing list of work orders entering Red Zone. This provides early warning to shop floor personnel on the need for intervention to ease any backlog.

With the use of BM as the only signalling system, backlog at a work centre will be reflected on all work orders requiring this resource. This offers system wide alert which can facilitate systemic approach to release backlog. In the event where solution to release backlog is beyond the given authority of shop floor personnel, issues can be referred to higher management proactively: *Escalate*.

As shown in *Figure 6.5 (d)*, the desired distribution is for majority of work orders to finish within *Yellow* Zone of the BM. Reasons for work orders completed in *Red* and *Black* zones can be recorded to facilitate continuous improvement: *Target*. With the above four functions of BM, it is able to provide necessary information to facilitate *High Execution*. This includes decision making on Order Release, Priority Dispatching and Buffer Utilisation.

The concept of *High Execution* implies the importance of human involvement. This is evident in the implementation of WLC in Company W. Other than the role of human in the daily updating and releasing of work orders, *human behaviour* is highlighted as one of the main factors which directly affects the productivity of each work centre. The company warned against configuration which could potentially introduce distorted and undesired human behaviour.

The potential contribution of this research to *Human Role* in PPC is further detailed in the next section.

6.4 Human Role in PPC

Unlike other PPC solutions, S-DBR emphasises *light planning* and *heavy execution*. As highlighted in section 6.3, for a *heavy execution* dependent PPC such as S-DBR to succeed, *human role* must be an integral part of PPC. In the previous S-DBR cases identified, integration of *human role* as part of the development and implementation process is not explicitly discussed. The framework developed in section 3.6.1

combines prior research in both human role (HR) and decision support system (DSS) in PPC. Based on the results and discussion in section 5.3.3, 4.4 and *Table 6.19*, S-DBR together with its elements can directly contribute towards all quadrants in the matrix of HR-DSS.

However, there are three quadrants which are not covered by generic S&T of S-DBR:

(i) Interpersonal - Level of Support,
(ii) Informational - Transparency, and
(iii)Informational - Autonomy.

The common trait between the three is the extensive involvement of *contextual knowledge*, particularly *tacit knowledge* embodied in the people within the organisation. These three quadrants have direct implication towards the *practicality* of the PPC system developed.

These are not achievable without the researcher being an integral part of the company and taking action to effect change. This leads to the next topic of discussion: Action Research (AR).

Table 6.19: Key Points Identified in the Development of an S-DBR based PPC Decision Support Tool for Amberol

	Level of Support	**Transparency**	**Autonomy**	**Information Presentation**
Interpersonal	• Should not be adding complexity and burden to existing workload. • Should be an integral part of day-to-day activity. • Facilitate communication	• Support personnel performance evaluation	• Encourage team work • Allow higher management to provide empowerment	• Dashboard • Graphical/Visual • Easy to understand • Easy to navigate • Job priorities are represented using five colours: *(i) blue*: to be pooled *(ii) green*: could choose to start if no other jobs which are more urgent *(iii) yellow*: start job *(iv) red*: expedite job *(v) black*: late
Informational	• Information on all job tickets in hand (In-Progress and In-Queue) • Auto-resource allocation (under normal condition) • Resource Utilisation • Workload per Standard Industrial Lead Time • Job Ticket Priority • Due date for confirmed orders to be based on current system loading • Job ticket status and progress • Allow proposed due date to be enquired based on current system loading • Allowed centralised work order information to be captured and shared on single platform by all departments	• Easy to understand PPC principles: *Time Buffer Management* for job priority • User defined Resource Loading algorithm • User defined Performance Target • User defined touch time (rough cut actual time worked on an item) • Product related Information/knowledge can be easily updated and proliferated	• Explicitly allow manipulation of capacity options/variables to simulate outcome: - Machines deployed - Machine performance - Additional mould deployment - Batch size • Information source traceability	
Decision Making	• To *Prioritise* • To *Expedite* • To *Escalate* if need higher management's attention • To *Target* areas requiring continuous improvement • Allow final resource assignment • Allow rescheduling			

Chapter 7: Conclusion

Simplicity is the ultimate sophistication

- Leonardo da Vinci

To conclude, this chapter will begin by providing a summary on the contribution of this research followed by a discussion of potential future research.

7.1 The Two Parallel Projects

This document is an illustration on how two projects: company project (CP) and research project (RP), have been successfully run together in parallel. The first project: company project, is a real-life project with a KTP (Knowledge Transfer Partnership) setup. This partnership is formed between the UK government, the company (Amberol), and NTU (across the Business School and School of Science and Technology). The KTP project outline involved the adoption of a Theory of Constraints (TOC) based PPC (Production Planning and Control) system to improve the operating performance of the company.

Acknowledging the importance of *fit* between contextual environment and *best practice*, the following research questions were formulated:

RQ1: What are the concepts underpinning S-DBR and how can they be configured to meet specific MTO contextual environments?

RQ2: What are the implementation issues in S-DBR and how are they addressed?

To explore the above RQs, chapter 2 begins by conducting a company diagnostic to provide an insight into the contextual manufacturing environment and challenges faced by the case company.

Having understood the company's contextual environment, Chapter 3 continues to explore the research questions through theoretical arguments. A review was conducted to identify the appropriate PPC for MTO environment advocated by academic researchers. From the review, it is found that although TOC based PPC applications have been practiced by practitioners since the 80s, its relevance to MTO manufacturing environment is still questioned by academics. Instead, Workload Control (WLC) has been reviewed to be the most appropriate PPC application in such environment. In addition, although the latest development of TOC in PPC applications, Simplified Drum-Buffer-Rope (S-DBR), has been introduced for more than fifteen years, it has received minimal attention by academic researchers.

With the attempt to explore and bridge this gap, chapter 3 continues to provide a critical review on the underpinning philosophy and implementation issues identified for TOC and WLC. At the end of the chapter, a conceptual framework was derived to underpin and guide the research project. As presented in section 3.8, the conceptual framework attempts to bridge the theoretical and practical aspects of this research. The theoretical aspect includes the underpinning concepts of the potential PPC solution (section 3.3 – 3.5), the potential challenges in implementation (section 3.6), and the performance measurements to be used to evaluate the intervention (section 3.7). The practical aspect encompasses the contextual requirements of the case company. The position of this research project (together with the RQs) is depicted in the conceptual framework as an attempt to conduct fit analysis, to capture the practical knowledge generated throughout the implementation process (*Figure 7.1*).

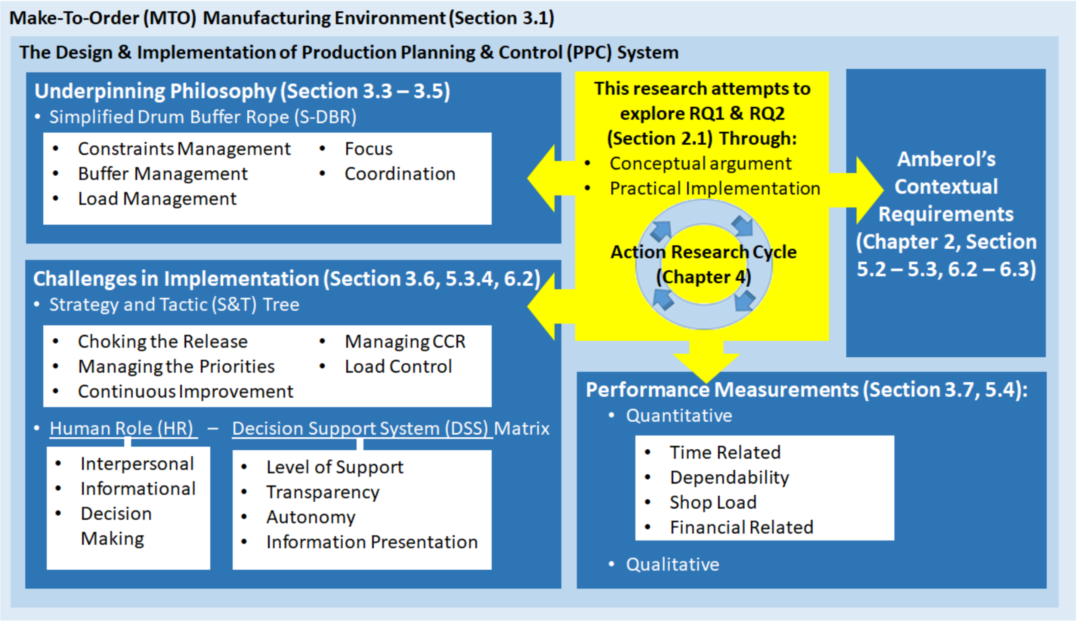


Figure 7.1: Conceptual Framework and RQs

In determining a suitable research methodology, an evaluation was conducted to achieve methodological fit. As detailed in chapter 4, the methodological fit is evaluated between the following key elements: *Research Question* (chapter 2 and section 4.2.2), *Contribution* (section 4.2.1), *Research Approach* (section 4.2.4), and *Maturity of Knowledge* (section 4.2.2 and 4.2.3). Action Research (AR) was determined to be an appropriate research approach to achieve the above methodological fit. This evaluation is further justified with the successful implementation of this project.

This project was primarily about *taking action* to effect *change*. The researcher, who worked as a business system architecture designer in the company, was tasked to manage the intervention process. As illustrated in Chapter 4, this involves taking actions through multiple AR cycles to effect change. Actions taken includes both the *hard* and *soft* aspects. *Hard* actions include the technical aspect of the S-DBR based PPC software development which requires full stack programming capabilities. The *soft* actions included the actions necessary to integrate the software into the daily work routine of the company's personnel. This required a holistic understanding acknowledging the existence of complexity within the.

This complexity includes both the formal and informal aspects of the organisation, such as the ethical framework, values and norms. This understanding forms *trust* between researcher and the organisation, which facilitates an *interactive research*. As shown in the various AR cycles in Section 4.2 and 4.3, the solution to problem is developed step-by-step, through iterative cycles with inputs from academic experts as well as industry, particularly the *tacit knowledge* from shop floor personnel.

This research has successfully explored the RQs through the dual goal of AR: problem solving and contribution to science. This coincides with the concept of *engaged scholar* advocated in this professional doctorate study: Doctoral in Business Administration (DBA). With reference to the discussion in section 5.4, both quantitative and qualitative evaluation demonstrates the significant positive contribution of this intervention towards the operating performance of the company: problem solving. An S-DBR based PPC software: *Visible*, has been successfully developed. Its usage has been extended beyond being a mere PPC software. Through the incorporation of *tacit knowledge*, it has been successfully turned into a decision support tool. The level of integration into the daily work routine of both manufacturing and non-manufacturing personnel is achieved by further developing Visible into a *communication platform*.

Financially, a year after implementation, the company successfully reduced its operating cost by half. Although sales turnover is the highest recorded in the past five years, with the help of *Visible*, for the first time, manufacturing department has the confidence to fulfil the sales orders using single shift throughout the year (where before this, two shifts were employed during peak season). This is achieved with 91.5% DDP (Due Date Performance) and 0.72% scrap. The threat of succession issue due to the retirement of the production manager has been successfully turned into an opportunity to introduce new working culture in the company.

The gradual and incremental approach taken in the change process has successfully turned Visible from a perceived *threat* of making shop floor personnel redundant into a *tool* to enhance their work performance. The improvement in internal coordination has enabled senior management to devote attention towards marketing related activities. This is evident from the increased sales turnover.

The second goal of AR: contribution to science, is well illustrated in Chapter 3 and 6. Based on the evaluation criteria proposed in the seminal work of Stevenson et al. (2005), S-DBR is re-evaluated using theoretical argument as a suitable PPC solution in MTO environment. Although it has been introduced in practice by the TOC (Theory of Constraints) community since year 2001, it has received relatively limited attention by researchers in academia. Considered as the third-generation development since the inception of OPT (Optimised Production Technology) in 1979 and DBR (Drum-Buffer-Rope) in 1984, S-DBR continues the move towards a simplified solution. It moves further away from *heavy planning* and adopted on *heavy execution*.

A critical review was conducted to compare S-DBR (advocated by practitioners) with WLC (Work Load Control), a PPC solution advocated by academia as most suitable in MTO environment. Although both solutions have different philosophical origins, they appear to converge when positioned on a *planning and execution spectrum*.

The TOC philosophy originated in OPT software which involves *heavy planning* and *light execution*. Over the years, realising and acknowledging the complexity of the MTO manufacturing environment, it has moved towards the opposite end of the spectrum.

WLC, started from a simple input-output control concept, has been developed towards *heavy planning* and *light execution*. This might be due to the different approach adopted in solution development. Practitioners have taken the systemic and pragmatic approach in solution development. Researchers from academia has taken the *local optima approach*, breaking down a system into smaller researchable parts in a simulated or *laboratory* environment. However, it is realised that the whole is greater than the sum of its parts. This might have contributed to the gap between academia and practice. Future research can be conducted to explore the use of concepts such as *Buffer Management* in S-DBR to increase the execution role within WLC.

In addition to the above insight, this research investigates existing WLC – DBR comparison studies. It is discovered that DBR is often reduced into a mere *bottleneck* solution. *Buffer Management*, a critical element within DBR solution is rarely discussed. In this document, all three *pillars* within S-DBR are highlighted: *Constraint Management*, *Load Management* and *Buffer Management*.

Through theoretical and conceptual argument, there are similarities exhibited between S-DBR and WLC in terms of *Constraint Management* and *Load Management*. However, as WLC adopts *light execution* approach, it only uses simple rules such as FIFO (First in First out) to progress work orders once it has been released onto the shop floor. In contrast, S-DBR uses *Buffer Management* as a simple signalling mechanism to provide constant monitoring of the work order. This includes functions: to *prioritise*, *expedite*, *escalate*, and *target*, which support further decision-making process in *execution*. The successful use of *Buffer Management* can be potentially adopted and be used in WLC and other PPC solutions.

To further explore the similarities between WLC and S-DBR, S-DBR was analysed using a WLC lens in section 3.4. This includes the *order release mechanism*, *workload consideration*, *capacity planning and schedule visibility*. Under this lens, S-DBR could be viewed as one of the *variants* within WLC. It could potentially be known as an S-DBR based WLC system.

The contribution towards science is also evident through RQ2. In the TOC practitioner world, a generic implementation guide on S-DBR is provided in the form of Strategy and Tactic (S&T) Tree, published by TOCICO (Theory of Constraints International Certification Organisation). As described in Section 3.3.6, each element within the

S&T tree records the result of inquiry process: *objective of a step, assumptions used,* and the *practical way to implement the step*. This generic S&T tree for S-DBR is adopted as the reference to inform this research project. The assumptions used in each step is challenged using the company's contextual environment. This *fit* is analysed in section 5.2.1 and summarised in *Table 5.1 and 5.2*. The analysis finds a non-fit in two major assumptions used. This is mainly due to the significance of touch time in total lead time, and the location of the potential CCR.

A review is conducted on empirical research cases published in academic journals. It is found that only two published journal articles have conducted generic S-DBR S&T tree based empirical research. A cross case analysis is conducted by placing Amberol alongside with the five companies reported in prior research. As detailed in both *Table 5.3* and *Table 6.5*, the contextual environment of Amberol challenges the various assumptions used in prior cases. This research offers opportunity to explore a relatively more complex environment.

Amberol has more than one potential CCR, has wandering bottleneck, as well as highly dependent sequence at CCR. The additional use of *Red Line*: the standard industry accepted delivery lead time, together with the plan load, successfully provides important indication for proactive actions to be taken. The successful implementation of this research potentially contributes towards the existing S-DBR body of knowledge in academia. Section 6.2 details how new mechanism has been developed to address the above challenges. The new assumptions and mechanisms are detailed in *Table 6.6*, placing the newly developed S&T for Amberol side by side with the generic S&T for S-DBR.

In addition to the above S-DBR or PPC concept related contextual environment issues, researchers have highlighted the essential role of human factor in the implementation of a practical PPC. As reviewed in section 3.6.1, ultimately, it is the *people* who manages the organisation and be accountable to organisation performance. Thus, it is necessary to develop PPC in view of the role of people who are involved in PPC related decision making. Drawing from literature from two perspectives: human role (HR) in PPC and decision support system (DSS) in PPC, a matrix is developed to guide the development and implementation of Visible in Amberol. The three HR aspects highlighted are *Interpersonal*, *Informational*, and *Decision Making*. These roles are placed in matrix against the four design aspects for DSS: *Level of Support*, *Transparency*, *Autonomy* and *Information Presentation*.

From the analysis and discussion in section 5.3.4 and section 6.4, S-DBR, with its underpinnings addresses many of the concerns highlighted in the *HR-DSS matrix*. However, three quadrants in the matrix require further development according to contextual requirements. These quadrants include *Interpersonal - Level of Support*, *Informational - Transparency*, and *Informational - Autonomy*. The importance of HR and DSS in PPC is evident in S-DBR as it advocates light planning and heavy execution. *Heavy Execution* requires interaction between S-DBR, HR, and DSS to arrive at a best ‘fit’ according to contextual environment. Due to the dynamicity of the contextual environment, it is suggested that the PPC solution developed has to be continuously adapted and improved to remain relevant. Further research can be conducted to provide PPC researchers and practitioners a generic PPC solution guide based on the HR-DSS matrix developed. This matrix can be further explored using other MTO PPC approach such as WLC-HR-DSS.

7.2 Potential Future Research

With respect to S-DBR related body of knowledge, it is necessary for more S-DBR implementation to be reported in academia. Given its *Low Planning* and *High Execution* PPC approach, it is not possible to solely rely on simulation to ascertain performance of this approach. Additional practical implementation of S-DBR in various contextual environment will be able to explore the necessary practical adaptation. The method of combining *sequencing* at potential CCR, aggregating buffer towards the end of work order, and suitable progress updating can be further trialled in MTO industries with high variability and uncertainties. This includes industries which manufactures one-off products, requiring design, and trial and error in its manufacturing process.

With reference to the discussion in section 6.3, it is evident that both WLC researchers and practitioners have inclination towards adopting *lower planning* and *higher execution*. Practical implementation can be done to incorporate concept of BM into LUMS (Lancaster University Management School) WLC. This could explore the potential use of BM as the unique signalling mechanism in WLC for work orders to be ‘pulled’ through the shop floor. Upon the setting of DD and PRD (Planned Release

Date), BM can be used to provide the order release and priority dispatch to shop floor personnel.

With regards to PPC implementation related research, human factor should continue to be explored. Emphasis could be placed to explore the use of *tacit knowledge* to inform the necessary PPC adaptation. This includes the process in which PPC is developed *of the people* and *for the people*. This also requires a new set of operating performance criteria to be introduced. Rather than merely relying on quantitative data, it is proposed that the success of PPC implementation could potentially include qualitative data. This is to capture the *perceived success* which might concern the *practicality* of a PPC implementation. For this purpose, the PPC-HR-DSS framework proposed in this research could potentially be further refined and explored.

In this research, trait of *trust* has been noticed in the relationships between the stakeholders. The stakeholders with direct involvement are: *the researcher*, *shop floor personnel*, *senior management*, and *non-shop floor personnel*. Mutual trust is necessary between the above stakeholders for a successful PPC implementation. Other than the exhibition of *trust* among people, there is also *trust* formed between PPC users and PPC system. As discussed in Section 3.6.1, *mistrust* and *distrust* is a challenge in the PPC/DSS system design and implementation. Through AR, and the researcher being the *creator* of the system, the *mistrust* and *distrust* has been potentially reduced by the development of *trust* between the user and the *creator* of the system. Further research can be conducted to investigate the dynamic of *trust* between various project stakeholders.

Lastly, the use of S&T tree as an AR tool can potentially be further explored. In this research, its *progressive inquiry* setup suits the AR emerging inquiry approach. However, this research has only used it as a tool to capture knowledge towards the end of the project. It could potentially be used as a companion tool in all cycles within the AR process. *Table 7.1* provides a summary on the contribution to science of this research and potential future research.

Table 7.1: Summary of Research Contribution to Science and Potential Future Research

Contribution of This Research		**Potential Future Research**
Areas	**Description**	
S-DBR	• Relatively more complex manufacturing environment than existing reported cases: significant touch time, wandering bottleneck, sequence dependent, parallel machine resource, and multi-level assembly. • Redesign Time Buffer and Due Date Determination process. • Use of Red Line to enable proactive decision making. • Use of heuristic algorithm to assist release mechanism and load balancing.	• Increase the practical implementation and reporting of S-DBR in various contextual environment in academic publication. • Explore various practical adaptation necessary to subordinate 'company operation' to 'market'.
WLC and other MTO PPC approach	• Increase practicality by lowering 'planning' and increasing responsibility on 'execution'. • Use of BM in S-DBR to align 'order release' and 'priority dispatch' in WLC.	• A practical implementation of BM with LUMS WLC. • Encourage cross-breed analysis between WLC and S-DBR/TOC. Practical implementation should be encouraged rather than mere simulation. This is due to the 'high execution' nature of S-DBR.
Human Factor	• The concept of 'Low Planning', 'High Execution' in MTO manufacturing environment increases the importance of 'Human Factor'. • PPC has to be developed into a decision support tool to assist human role in an organisation. • New working culture has been developed with the implementation of Visible software. • Element of 'trust' is exhibited among project/research stakeholders. For a successful PPC/DSS system implementation, 'Mistrust' and 'Distrust' is a challenge to be addressed.	• Human factor is encouraged to be an integral part of all PPC implementation related research. • Explore how PPC is assimilated into organisation, forming part of 'tacit knowledge' in the organisation. This might be the missing link between theory and practice. • Encourage the use of qualitative data in the evaluation of success PPC implementation. • To understand the dynamics of 'trust' in a successful implementation of PPC/DSS system through AR.
Generic guide to develop MTO PPC tool	• An S-DBR-HR-DSS tool has been developed to guide the development and implementation of a practical PPC system.	• More specific guide/reference could be provided in each quadrant in the matrix. • To generalise, terminology and concept could be developed to represent the relationship behind each quadrant.
Research Approach		• Explore the use of S&T tree as an AR tool.

References

Ahlström, P. (2016), The research process. *In:* Karlsson, C., eds., *Research Methods for Operations Management.* 2nd Ed. New York: Routledge, pp. 46-78.

Adler, N. and Shani, A.B. (2001). In search of an alternative framework for the creation of actionable knowledge: Table-tennis research at Ericsson. *In:* Pasmore, W. and Woodman, R.W. eds., *Research in Organizational Change and Development*. Vol. 13 Greenwich, CT: JAI, 2001, pp. 43-79.

Allison, I., Stratton, R. and Robey, D., 2012. Addressing Food Production Planning and Control Issues through Information Visualisation: An Agile Development, *Communications of the IIMA,* 12(1), Article 1.

Amaro, G., Hendry, L. and Kingsman, B., 1999. Competitive advantage, customisation and a new taxonomy for non-make-to-stock companies. *International Journal of Operations & Production Management*, 19 (4), 349-371.

Anderson, N., Herriot, P. and Hodgkinson, G., 2001. The practitioner- researcher divide in industrial, work and organizational (IWO) psychology: Where are we now, and where do we go from here? *Journal of Occupational and Organizational Psychology,* 74, 391-411.

Argyris, C., 2005. Actionable Knowledge. *In:* C. Knudsen, and H. Tsoukas, eds., *The Oxford Handbook of Organization Theory.* New York: Oxford University Press, 2005, pp. 424-452.

Arica, E., Haskins, C., and Strandhagen, O., 2016. A framework for production rescheduling in sociotechnical manufacturing environments, *Production Planning & Control*, 27(14), pp. 1191-1205.

Arica, E., Strandhagen, J.O., and Hvolby, H., 2014. Designing a Decision Support System for Production Scheduling Task in Complex and Uncertain Manufacturing Environments. In: Grabot, B., Vallespir, B., Gomes, S., Bouras, A., Kiritsis, D., eds., *Advances in Production Management Systems. Innovative and Knowledge-Based Production Management in a Global-Local World*. *APMS 2014. IFIP Advances in Information and Communication Technology,* 438. Springer, Berlin, 2014, pp. 589 – 596.

Balderstone, S.J. and Mabin, V.J., 1998. A review of Goldratt’s theory of constraints (TOC): lessons from the international literature, Proceedings of the 33rd Annual Conference of the Operational Research Society of New Zealand, Auckland, pp. 205-14.

Barnard, A., 2010. Continuous Improvement and Auditing. *In:* J.F. Cox, and G. Schleier, eds., *Theory of Constraints Handbook.* McGraw-Hill, 2010, pp. 403-454.

Bechte, W., 1994. Load-oriented manufacturing control just-in-time production for job shops, *Production Planning & Control*, 5(3), pp. 292-307.

Bechte, W., 1988. Theory and practise of load-oriented manufacturing control, *International Journal of Production Research*, 26(3), pp. 375-395.

Bechte, W., 1982. Controlling manufacturing lead time and work-in-process inventory by means of load-oriented order release, *American Production and Control Inventory Society*, pp. 67-71.

Beckhard, R., and Harris, R., 1987. *Organizational Transitions: Managing Complex Change*. 2nd ed. Reading: Addison-Westley.

Beemsterboer, B., Land, M.J. and Teunter, R., 2016. Hybrid MTO-MTS production planning: An explorative study, *European Journal of Operational Research*, 248 (2), pp. 453-461.

Behrman, J.N., and Levin, R.I., 1984. Are business schools doing their job?. *Harvard Business Review,* 62 (1), pp. 140-147.

Benavides, M. B. and Van Landeghem, H., 2015. Implementation of S-DBR in four manufacturing SMEs: a research case study, *Production Planning & Control*, 26(13), pp. 1110-1127.

Bendoly, R., Croson, R., Goncalves, P., and Schultz, K., 2010. Bodies of Knowledge for Research in Behavioral Operations, *Production and Operations Management*, 19(4), pp. 434-452.

Bergamaschi, D., Cigolini, R., Perona, M. and Portioli, A., 1997. Order review and release strategies in a job shop environment: A review and a classification, *International Journal of Production Research*, 35(2), pp. 399-420.

Berglund, M., Guinery, J., and Karltun, J., 2011. The Unsung Contribution of Production Planners and Schedulers at Production and Sales Interfaces. In: Fransoo, J.C., Wafler, T. and Wilson, J., eds., *Behavioural Operations in Planning and Scheduling*. Berlin: Springer, 2011, pp. 47-81.

Berglund, M., and Guinery, J., 2008. The Influence of Production Planners and Schedulers at Manufacturing and Commercial Interfaces, 18(5), pp. 548-564.

Berglund, M. and Karltun, J., 2007. Human, technological and organizational aspects influencing the production scheduling process, *International Journal of Production Economics*, 110, pp. 160-174.

Bertrand, J.W.M., 1983. The effect of workload dependant due-dates on job-shop performance, *Management Science*, 29(7), pp. 799-816.

Bertrand, J.W.M. and Van Ooijen, H.P.G., 2002. Workload based order release and productivity: a missing link, *Production Planning & Control*, 13(7), pp. 665-678.

Bertrand, J.W.M. and Wortmann, J.C., 1981. Production control and information systems for component-manufacturing shops. Amsterdam: Elsevier

Betterton, C.E. and Cox III, J.F., 2009. Espoused drum-buffer-rope flow control in serial lines: A comparative study of simulation models, *International Journal of Production Economics*, 117, pp. 66-79.

Black, T.R., 1999. *Doing Quantitative Research in the Social Sciences: An Integrated Approach to Research Design, Measurement and Statistics.* 1st ed. SAGE Publications Ltd.

Blackstone, J.H., 2010. A Review of Literature on Drum-Buffer-Rope, Buffer Management and Distribution. In: Cox, J. F. and Schleier, J. G., eds., *Theory of Constraints Handbook*. United States of America: McGraw Hill, 2010, pp. 143-173.

Boer, H., Holweg, M., Kilduff, M., Pagell, M., Schmenner, R., and Voss, C., 2015. Making a meaningful contribution to theory, *International Journal of Operations & Production Management*, 35(9), pp. 1231-1252.

Bond, T.C., 1993. An investigation into the use of OPT production scheduling. *Production Planning and Control,* 4(4), pp. 399-406.

Bonney, M., 2000. Reflections on Production Planning and Control (PPC), *Gestáo & Producáo*, 7(3), pp. 181-207.

Boyd, L., and Gupta, M., 2004. Constraints management: What is the theory? *International Journal of Operations & Production Management*, 24 (4), 350-371.

Boyer, E.L., 1996. The Scholarship of Engagement. *Bulletin of the American Academy of Arts and Sciences*, 49 (7), pp. 18-33.

Breithaupt, J., Land, M.J., and Nyhuis, P., 2002. The workload control concept: theory and practical extensions of Load Oriented Order Release, *Production Planning & Control*, 2002, 13(7), pp. 625-638.

British Plastic Federation, 2018. *Rotational Moulding*. BPF. [Online] Accessible at: http://www.bpf.co.uk/Plastipedia/Processes/Rotational_Moulding.aspx [Accessed 13 December 2018]

Brocklesby, J., 2016. The what, the why and the how of behavioural operational research – An invitation to potential sceptics, *European Journal of Operational Research*, 249, pp. 796-805.

Bryman, A., 2004. Social Research Methods. 2nd ed. New York: Oxford University Press Inc.

Bylinski, G., 1983. An efficiency guru with a brown box. *Fortune*, Vol. 108, pp. 120–132.

Carmo-Silva, S. and Fernandes, N. O., 2017. Bottleneck-Oriented Release: An Assessment by Simulation, *WorldCIST 2017: Recent Advances in Information Systems and Technologies*, 570, pp. 406-415.

Chakravorty, S. S. and Hales, D. N., 2016. Improving labour relations performance using a Simplified Drum Buffer Rope (S-DBR) technique, *Production Planning & Control*, 27(2), pp. 102 - 113.

Chang, Y. and Huang, W., 2014. An enhanced model for SDBR in a random re-entrant flow shop environment, *International Journal of Production Research*, 52(6), pp. 1808-1826.

Cigolini R. and Portioli-Staudacher, A., 2002. An experimental investigation on workload limiting methods within ORR policies in a job shop environment, *Production Planning & Control*, 13(7), pp. 602-613.

Coghlan, D., 2011. Action Research: Exploring Perspectives on a Philosophy of Practical Knowing. *The Academy of Management Annals*, 5 (1), pp. 53-87.

Cohen, W.M., Florida, R., Randazzese, L. and Walsh, J., 1998. Industry and the Academy. *In:* R.G. Noll, ed., *Challenges to Research Universities.* Washington, D.C.: Brookings Institution, 1998, pp. 171-199.

Coghlan, D., 2010. Seeking Common Ground in the Diversity and Diffusion of Action Research and Collaborative Management Research Action Modalities: Toward a General Empirical Method. Emerald Group Publishing Limited, 2010, pp. 149-181.

Coghlan, D., 2007. Insider action research doctorates: Generating actionable knowledge. *Higher Education*, 54, pp. 293-306.

Coghlan, D., 2001. Insider Action Research Projects: Implications for Practicing Managers. *Management Learning*, 32 (1), pp. 49-60.

Coghlan, D., and Brannick, T., 2014. *Doing action research in your own organization.* Fourth Edition. London: Sage Publications Ltd.

Coghlan, D., and Shani, A., 2014. Creating Action Research Quality in Organization Development: Rigorous, Reflective and Relevant. *Systemic Practice & Action Research*, 27 (6), pp. 523-536.

Cooper, D.R., and Schindler, P.S., 2008. *Business Research Methods.* 10th ed. Singapore: McGraw-Hill.

Coughlan, P., and Coghlan, D., 2016. Action Research. *In:* Karlsson, C., eds., *Research Methods for Operations Management.* 2nd Ed. New York: Routledge, pp. 233-267.

Coughlan, P., and Coghlan, D., 2002. Action research for operations management. *International Journal of Operations & Production Management,* 22 (2), pp. 220-240.

Costley, C., and Lester, S., 2012. Work-based Doctorates: Professional Extension at the Highest Levels. *Studies in Higher Education,* 37 (3), pp. 257-269.

Cox III, J. F., Boyd, L. H., Sullivan, T. T., Reid, R. A., Cartier, B., 2012. *The Theory of Constraints International Certification Organization Dictionary*, *Second Edition* [online]. Washington: TOCICO. Available at: http://www.tocico.org/?page=dictionary [Accessed 3 May 2016].

Cox, J.F., Schleier, J., and Cox III, J.C., 2010. Theory of Constraints Handbook. McGraw-Hill.

Crawford, S. and Wiers, V.C.S., 2001. From Anecdotes to Theory: A Review of Existing Knowledge on Human Factors of Planning and Scheduling. In: MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling.* London: Taylor and Francis, 2001, pp.15–43.

Crawford, S., 2001. Making Sense of Scheduling: The Realities of Scheduling Practice in and Engineering Firm. In: MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling.* London: Taylor and Francis, 2001, pp. 83–104.

David, A., and Hatchuel, A., 2008. From Actionable Knowledge to Universal Theory. In: A.B. Shani, S. Mohrman, W. Pasmore, B. Stymne and N. Adler, eds., *Handbook of Collaborative Management Research.* Thousand Oaks, CA: Sage, 2008, pp. 33-47.

Davies, J., Mabin, V.J., and Balderstone, S.J., 2005, The theory of constraints: a methodology apart? – a comparison with selected OR/MS methodologies, *Omega The International Journal of Management Science*, 33, pp. 506 – 524.

DBA, 2015. *Course Handbook - Cohort 17.* Nottingham: Nottingham Business School.

Deblaere, F., Demeulemeester, E., Herroelen, W., and Van de Vonder, S., 2007. “Robust Resource Allocation Decisions in Resource-Constrained Projects”, *Decision Sciences*, 38(1), pp. 5 – 37.

Dettmer, H. W., 2007. *The Logical Thinking Process: A systems approach to complex problem solving.* ASQ Quality Press.

Doncaster, K., and Lester, S., 2002. Capability and its development: Experiences from a work- based doctorate. *Studies in Higher Education*, 27 (1), pp. 91-101.

Done, A., Voss, C. and Rytter, N.G., 2011. Best practice interventions: Short-term impact and long-term outcomes. *Journal of Operations Management*, 29 (5), pp. 500 – 513.

Eden, C. and Huxham, C., 1996. Action Research for Management Research, *British Journal of Management*, 7, pp. 75 – 86.

Enns, S.T. and Costa, M.P., 2002. The effectiveness of input control based on aggregate versus bottleneck workloads, *Production Planning & Control*, 13(7), pp. 614-624.

Fernandes, N.O., Land, M.J., Carmo-Silva, S., 2014. Workload control in unbalanced job shops, *International Journal of Production Research*, 52(3), pp. 679 – 690.

Flynn, B.B., Sakakibara, S., Schroeder, R.G., Bates, K.A. and Flynn, E.J., 1990. Empirical research methods in operations management. *Journal of Operations Management*, 9 (2), 250-284.

Fransoo, J.C. and Wiers, V.C.S., 2008. An empirical investigation of the neglect of MRP information by production planners, *Production Planning & Control*, 19(8), pp. 781 – 787.

Fransoo, J.C. and Wiers, V.C.S., 2006. Action variety of planners: Cognitive load and requisite variety, *Journal of Operations Management*, 24, pp. 813 – 821.

Fredendall, L.D., Ojha, D., and Patterson, J.W., 2010. Concerning the theory of workload control, *European Journal of Operational Research*, 201, pp. 99 -111.

Fry, T.D., 1990. Controlling Input: The Real Key to Shorter Lead Times, *The International Journal of Logistics Management*, 1(1), pp. 7-12.

Fry, T.D., Cox III, J.F. and Blackstone, Jr., J.H., 1992. An analysis and discussion of the optimized production technology software and its use, *Production and operations Management*, 1(2), pp. 229-242.

Gardiner, S.C., Blackstone Jr., J.H., 1991. The 'Theory of Constraints' and the make-or-buy decision. *International Journal of Purchasing and Materials Management,* 27(3), pp. 38-43.

Gasser, R., Fischer, K. and Wafler, T., 2011. Decision Making in Planning and Scheduling: A Field Study of Planning Behaviour in Manufacturing. *In:* Fransoo, J.C., Wafler, T. and Wilson, J., eds., *Behavioral Operations in Planning and Scheduling*. Berlin: Springer. pp. 3-10.

Gelders, L.F. and Van Wassenhove, L.N., 1982. Hierarchical Integration in Production Planning: Theory and Practice. *Journal of Operations Management*. 3(1), pp. 27-35.

Gephart Jr., R.P., 2004. *Qualitative Research and the Academy of Management Journal.* Academy of Management.

Gibbons, M.L., Limoges, H., Nowotny, S., Schwartman, P., Scott, P. and Trow, M., 1994. *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies.* London: Sage.

Glassey, C.R. and Resende, M.G.C., 1988. Closed-Loop Job Release Control for VLSI Circuit Manufacturing, *IEEE Transactions on Semiconductor Manufacturing*, 1(1), pp. 36-46.

Goldratt, E.M., 2009. Standing on the Shoulders of Giants – Production concepts versus production applications The Hitachi Tool Engineering example, *Gestao & Producao*, 16(3), pp. 333-343.

Goldratt, E.M., Goldratt, R., Abramov, E., 2002. Strategy and Tactics [online]. Available at https://public.wsu.edu/~engrmgmt/holt/em534/Goldratt/Strategic-Tactic.html [Accessed 29th November 2018]

Goldratt, E.M., 1997. *Critical Chain*. North River Press, Great Barrington, MA.

Goldratt, E.M., 1994. *It's not luck*. North River Press, Great Barrington, MA.

Goldratt, E.M., 1990. *The Haystack Syndrome: Sifting Information Out of the Data Ocean*. North River Press, Great Barrington, MA.

Goldratt, E.M., 1988b. Computerized shop floor scheduling. *International Journal of Production Research*, 26(3), pp. 443–455.

Goldratt, E.M. and Fox, R.E., 1986. *The Race*. Great Barrington, MA: North River Press.

Goldratt, E.M. and Cox, F., 1984. *The Goal: Excellence in Manufacturing*. Croton-on-Hudon, NY: The North River Press.

Goldratt, E.M., 1981. The unbalanced plant. *In*: APICS 24th Annual International Conference Proceedings, APICS, Falls Church, VA.

Goldratt, E.M., 1980. Optimized production timetables: a revolutionary program for industry. *In*: APICS 23rd Annual International Conference, APICS, Falls Church.

Gonzalez-Benito, J., and Lannelongue, G., 2014. An integrated approach to explain the manufacturing function's contribution to business performance. *International Journal of Operations & Production Management,* 34 (9), pp. 1126 – 1126.

Gray, D.E., Iles, P. and Watson, S., 2011. Spanning the HRD academic- practitioner divide: bridging the gap through mode 2 research. *Journal of European Industrial Training,* 35 (3), 247-263.

Greenwood D.J., 2002. Action research: Unfulfilled promises and unmet challenges. *Concepts and Transformation,* 7 (2), 117-139.

Gummesson, E., 2000. *Qualitative methods in management research.* 2nd ed. Thousand Oaks; London: Thousand Oaks; London : Sage.

Gupta, M. and Boyd, L., 2011. An Excel- based dice game: an integrative learning activity in operations management. *International Journal of Operations & Production Management,* 31(6), 608-630.

Gupta, M.C. and Boyd, L.H., 2008. Theory of constraints: a theory for operations management, *International Journal of Operations & Production Management,* 28(10), pp. 991-1012.

Gupta, M.C., 2003. Constraints management – recent advances and practices, *International Journal of Production Research,* 41(4), pp. 647 – 659.

Gustavsen B., 2003a. Action research and the problem of the single case. *Concepts and Transformation,* 8 (1), 93-99.

Gustavsen, B., 2003b. New Forms of Knowledge Production and the Role of Action Research. *Action Research,* 1 (2), 153-164.

Harmony, 2017. What is Strategy & Tactic Trees? [Online]. Harmony. Available at: https://www.harmonytoc.com/What-Is-TOC-Strategy-and-Tactic-Trees [Accessed 12th December 2017].

Harvey, H., 2001. Boundaries of the Supervisory Role and their Impact on Planning and Control, *In:* MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling.* London: Taylor and Francis, pp.105-133.

Hayes, R.H. and Pisano, G.P., 1994. Beyond World-Class: The New Manufacturing Strategy. (Cover Story). *Harvard Business Review,* 72 (1), pp. 77-87.

Hendry, L., Huang, Y., and Stevenson, M., 2013. Workload control: Successful implementation taking a contingency-based view of production planning and control, *International Journal of Operations & Production Management,* 33(1), pp. 69-103.

Hendry, L., Land, M.J., Stevenson, M. and Gaalman, G., 2008. Investigating implementation issues for workload control (WLC): A comparative case study analysis, *International Journal of Production Econmics,* 112, pp. 452-469.

Hendry, L., B. G. Kingsman, and Cheung, P., 1998. The effect of workload control (WLC) on performance in make-to-order companies, *Journal of Operations Management*, 16, pp. 63-75.

Hendry, L. and Kingsman, B. G., 1993. Customer Enquiry Management: Part of a Hierarchical System to Control Lead Times in Make-To-Order Companies, *The Journal of the operational Research Society*, 44(1), pp. 61-70.

Hendry, L. and Kingsman, B., 1991. A Decision Support System for Job Release in Make-to-order Companies, *International Journal of Operations & Production Management*, 11(6), pp. 6-16.

Hendry, L. and Kingsman, B., 1989. Production planning systems and their applicability to make-to-order companies, *European Journal of Operational Research*, 40, pp. 1-15.

Henrich, P., Land, M.J., Gaalman, G., 2004. Exploring applicability of the workload control concept, *International of Production Economics*, 90, pp. 187-198.

Higgins, P.G., 2001. Architecture and Interface Aspects of Scheduling Decision Support. *In:* MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling.* London: Taylor and Francis, pp. 245-279.

Hinings, C.R., and Greenwood, R., 2002. ASQ Forum: Disconnects and Consequences in Organization Theory. *Administrative Science Quarterly*, 47 (3), 411-421.

Hopp, W. J. and Spearman, M. L., 2004. To Pull or Not to Pull: What Is the Question?, *Manufacturing & Service Operations Management*, 6(2), pp. 133-148.

Huang, Y., 2017. Informaiton architecture for effective Workload Control: an insight from a successful implementation, *Production Planning & Control*, 28(5), pp. 351-366.

Huff, A.S., and Huff, J.O., 2001. Re-Focusing the Business School Agenda. *British Journal of Management*, 12, S49.

Hwang, Y. L., C. Huang, and R. K. Li., 2011. Using Simplified Drum-Buffer-Rope to Rapidly Improve Operational Performance: A Case Study in China. *Production and Inventory Management Journal*, 47(1), pp. 80-93.

Inherent Simplicity, 2010. *Managing high touch-time environments in S-DBR*. TOCICO. [online] Accessible at https://cdn.ymaws.com/www.tocico.org/resource/resmgr/2010_conf_pres/schragenheim__amir_2010_pres.pdf [Accessed 29th November 2018].

Jackson, S., Wilson, J.R. and MacCarthy, B.L, 2004. A New Model of Scheduling in Manufacturing: Tasks, Roles, and Monitoring, *Human Factors*, Vol. 46, No.3, pp. 533-550.

Johnson, D.S., Perlow, R., and Pieper, K.F., 1993. Differences in task performance as a function of type of feedback: Learning-oriented versus performance-oriented feedback, *Journal of Applied Social Psychology*, 23(4), pp.303-320.

Johnson, H.T., Kaplan, R.S., 1987. Relevance Lost: The Rise and Fall of Management Accounting. Harvard Business School Press, Boston, MA.

Karlsson, C., 2016. Research in Operations Management. *In:* C. Karlsson, ed., *Research Methods for Operations Management*. 2nd ed. New York: Routledge, 2016a, pp. 7-45.

Karltun, J. and Berglund, M., 2010. Contextual conditions influencing the scheduler's work at a sawmill, *Production Planning & Control*, 21(4), pp. 359-374.

Kikoski, C. K. and Kikoski, J. F., 2004. *The Inquiring organization: Tacit Knowledge, Conversation, and Knowledge Creation Skills for 21st-Century Organizations*. Praeger, Westport, CT and London.

Kim, S., Mabin, V.J. and Davies, J., 2008. The theory of constraints thinking processes: retrospect and prospect, *International Journal of Operations & Production Management*, 28(2), pp. 155-184.

Kingsman, B. G. and Hendry, L., 2002. The relative contributions of input and output controls on the performance of a workload control system in Make-To-Order companies, *Production Planning & Control*, 13(7), 579-590

Kingsman, B. G., 2000. Modelling input-output workload control for dynamic capacity planning in production planning systems, *International Journal of Production Economics,* 68, pp. 73-93.

Kingsman, B. G., Hendry, L., Mercer, A., and de Souza, A., 1996. Responding to customer enquiries in make-to-order companies – Problems and solutions, (46-47), pp. 219-231.

Kingsman, B.G., Tatsiopoulos, I.P. and Hendry, L.C., 1989. A structural methodology for managing manufacturing lead times in make-to-order companies, *European Journal of Operational Research*, 40, pp. 196-209.

Klein, M. and Methlie, L.B., 1990. *Expert systems, a decision support approach with applications in management and finance,* Addison Wesley, Reading MA.

Kleinmuntz, B., 1990. Why we still use our heads instead of formulas: Toward an integrative approach. *Psychological Bulletin*, 107(3), pp. 296-310.

Land, M.J., 2006. Parameters and sensitivity in workload control, *International Journal of Production Economics,* 104, pp. 625-638.

Land, M.J., 2004. Workload control in job shops, grasping the tap. Labyrinth, Ridderkerk

Land, M. J., Stevenson, M., and Thurer, M., 2014. Integrating load-based order release and priority dispatching, *International Journal of Production Research*, 52(4), pp. 1059-1073.

Land, M. J. and Gaalman, G., 2009. Production planning and control in SMEs: time for change, *Production Planning and Control*, 20(7), pp. 548-558.

Land, M. J. and Gaalman, G., 1998. The performance of workload control concepts in job shops: Improving the release method, *International Journal of Production Economics*, 56-57, pp. 347-364.

Land, M. J. and Gaalman, G., 1996. Workload control concepts in job shops: A critical assessment, *International Journal of Production Economics*, 46, pp. 535-548.

Laudon, K.C. and Laudon, J.P., 2002. *Management information systems*, Prentice Hall Inc, New Jersey.

Lawrence, S.R., Buss, A.H., 1994. Shifting production bottlenecks: causes, cures, and conundrums. *Production Operation Management,* 3(1), pp. 21–37

Lee, J.D. and See, K.A., 2004. Trust in Automation: Designing for Appropriate Reliance, *Human Factors,* 46(1), pp. 50-80.

Lee, J., Chang, J., Tsai, C. and Li., R., 2010. Research on enhancement of TOC Simplified Drum-Buffer-Rope system using novel generic procedures, *Expert Systems with Applications,* 37, pp. 3747-3754.

Lee, T.W., Mitchell, T.R. and Sablynski, C.J., 1999. Qualitative Research in Organizational and Vocational Psychology, 1979–1999. *Journal of Vocational Behavior,* 55 (2), pp. 161-187.

Levin, M., and Greenwood, D.J., 2008. The Future of Universities: Action Research and the Transformation of Higher Education. In: Reason, P. and Bradbury, H., eds., *The SAGE Handbook of Action Research.* Sage Publications Ltd, 2008, pp. 211-226.

Lewin, K., 1946. Action research and minority problems, *Journal of Social Issues,* 2 (4), pp. 34-46.

Lingayat, S., Mittenthal, J., O'Keefe, R.M., 1995. Order Release in Automated Manufacturing Systems, *Decision Science*, 26(2), pp. 175-207.

Liu. H. X., 2012. A dynamic bottleneck-oriented manufacturing control. GITO mbH Verlag, Berlin.

Mabin, V.J. and Balderstone, S.J., 2003. The performance of the theory of constraints methodology: analysis and discussion of successful TOC applications, *International Journal of Operations & Production Management*, 23(6), pp. 568-595.

Mabin, V.J., Forgeson, S., and Green, L., 2001. Harnessing resistance: using the theory of constraints to assist change management, 25(2), pp. 168-191.

Mabin, V.J. and Balderstone, S.J., 2000. The World of the Theory of Constraints: A Review of the International Literature, St. Lucie Press, Boca Raton, FL.

MacCarthy, B.L., Wilson, J.R. and Crawford, S., 2001. Human Performance in Industrial Scheduling: A Framework for Understanding, *Human Factors and Ergonomics in Manufacturing*, 11(4), pp. 299-320.

MacCarthy, B.L. and Wilson, J.R., 2001. The Human Contribution to Planning, Scheduling and Control in Manufacturing Industry – Background and Context. In: MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling.* London: Taylor and Francis, 2001, pp. 3-14.

MacLean, D., MacIntosh, R. and Grant, S., 2002. Mode 2 Management Research. *British Journal of Management,* 13 (3), pp. 189-207.

Manathunga, C., Smith, C. and Bath, D., 2004. Developing and evaluating authentic integration between research and coursework in professional doctorate programs. *Teaching in Higher Education,* 9 (2), pp. 235-246.

McCutcheon, D.M., and Meredith, J.R., 1993. Conducting case study research in operations management. *Journal of Operations Management,* 11 (3), pp. 239-256.

McKay, K.N., Pinedo, M., and Webster, S., 2002. Practice-focused research issues for scheduling systems, *Production and Operations Management*, 11(2), pp. 249-258.

McKay, K.N., Wiers, V.C.S., 2001. Decision support for production scheduling tasks in shops with much uncertainty and little autonomous flexibility. In: MacCarthy, B., Wilson, J., eds., Human Performance in Planning and Scheduling. Taylor and Francis, New York, pp. 165-178

McKay, K.N. and Wiers, C.S.V., 1999. Unifying the Theory and Practice of Production Scheduling, *Journal of Manufacturing Systems*, 18(4), pp. 241-255.

McKay, K.N. and Buzacott, J.A., 2000. The application of computerized production control systems in job shop environments, *Computer in Industry*, 42, pp. 79-97.

McKay, K.N., 2001. Lessons from the Factory Floor. *In:* MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling*. London: Taylor and Francis, pp. 45–64.

Melnyk, S.A. and Ragatz, G.L., 1989. "Order review/release: research issues and perspectives, *International Journal of Production Research*, 27(7), pp. 1081-1096.

Mezirow, J., 1997. *Transformative Dimensions of Adult Learning*. San Francisco: Jossey-Bass.

Mokotoff, E., 2001. Parallel Machine Scheduling Problems: A Survey, *Asia-Pacific Journal of Operational Research*, 18(2), pp. 193-242.

Muir, B.M. and Moray, N. (1996), "Trust in automation part II: experimental studies of trust and human intervention in a process control simulation", *Ergonomics*, 39(3), pp. 429-460.

Mula, J., Poler, R., Garcia-Sabater, J. P. and Lario, F. C., 2006. Models for production planning under uncertainty: A review, *International Journal of Production Economics*, (103), pp. 271-285.

Nakamura, N. and Salvendy, G., 1994. Human Planner and Scheduler. In: Salvendy, G. and Karwowski, W., eds., *Design of work and development of personnel in advanced manufacturing*. New York: J. Wiley, 1994, pp. 331-354.

Nonaka, I., Toyama, R. and Konno, N, 2000. SECI, *Ba* and Leadership: a Unified Model of Dynamic Knowledge Creation. Long Range Planning, 33, pp. 5-34.

Norman, D.A., 1988. *The psychology of everyday things*, Basic Books Inc., New York.

Nowotny, H., 2000. *Re-thinking science: knowledge and the public in an age of uncertainty*. Polity P.

Olhager, J. 2003). Strategic positioning of the order penetration point, *International Journal of Production Economics*, 85, pp.319-329.

OMBOK, 2016. *APICS OMBOK Framework 4.2* [online]. APICS. Available at: http://www.apics.org/industry-content-research/publications/ombok/apics-ombok-framework-table-of-contents/apics-ombok-framework-4.2 [Accessed 24th April 2016].

Oosterman, B., Land, M.J., and Gaalman, G., 2000. The influence of shop characteristics on workload control. *International Journal of Production Economics*, 68, pp. 107-119.

Osteryoung J. S., McCarthy, D.E., and Reinhart, W.J., 1986. Use of EOQ Model for Inventory Analysis. *Production and Inventory Management Journal*. 3, pp. 39-45.

Ozdamar, L. and Yazgac, T., (1997. Capacity driven due date settings in make-to-order production systems", *International Journal of Production Economics*, 49, pp. 29-44.

Parente, D. H. (1998), "Across the manufacturing-marketing interface Classification of significant research", *International Journal of Operations & Production Management*, 18(12), pp. 1205-1222.

Parkinson, C. N. (1955), "Parkinson's Law", *The Economist*, 177, pp. 635-637. [Available via: https://www.economist.com/news/1955/11/19/parkinsons-law [Accessed 30th June 2019].

Perry, C., and Zuber-Skerritt, O., 1994. Doctorates by Action Research for Senior Practicing Managers. *Management Learning*, 25 (2), pp. 341-364.

Philipoom, P.R. and Fry, T.D. 1992, Capacity-based order review/release strategies to improve manufacturing performance. *International Journal of Production Research*, 30(11), pp. 2559-2572.

Philipoom, P.R., Malhotra, M.K., and Jensen, B., 1993. An Evaluation of Capacity Sensitive Order Review and Release Procedures in Job Shops. *Decision Sciences*, 24(6), pp. 1109-1133.

Pinedo, M., 2008. *Scheduling: Theory, Algorithms and Systems*. 3rd ed. New York: Springer.

Polanyi, M., 1966. *The Tacit Dimension*. 1st Edition, New York: Doubleday & Company Inc.

Porter, L.W., and McKibbin, L.E., 1988. *Management Education and Development: Drift or Thrust into the 21st Century*. New York: McGraw-Hill.

Rahman, S., 1998. Theory of constraints: a review of the philosophy and its applications. *International Journal of Operations & Production Management*, 18(4), pp. 336-355.

Raelin, J., 2015. Action Modes of Research. *In:* L. Anderson, J. Gold, J. Steward and R. Thorpe, eds., *A Guide to Professional Doctorates in Business & Management.* Sage, 2015, pp. 57-76.

Ragatz, G. L. and Mabert, V. A., 1984. A framework for the study of due date management in job shops. *International Journal of Production Research*, 22(4), pp. 685-695.

Reason, P., 2006a. Choice and Quality in Action Research Practice. *Journal of Management Inquiry,* 15 (2), pp. 187-203.

Reason, P., 2006b. A Response to J.A. McKernan. *Journal of Management Inquiry,* 15 (2), pp. 207-208.

Revans, R.W., 1971. *Developing Effective Managers.* New York: Praeger Publisher.

Riezebos, J., Korte, G.J. and Land, M.J., 2003. Improving a practical DBR buffering approach using Workload Control. *International Journal of Production Research,* 41(4), pp. 699-712.

Roderick, L.M., Phillips, D.T. and Hogg, G.L.. 1992. A comparison of order release strategies in production control systems. *International Journal of Production Research*, 30(3), pp. 611-626.

Romero-Silva, R., Santos, J., and Hurtado, M., 2015. A framework for studying practical production scheduling. *Production Planning & Control*, 26(6), pp. 438-450.

Rynes, S.L., Bartunek, J.M., and Daft, R.L., 2001. Across the great divide: Knowledge Creation and Transfer between Practitioners and Academics. *Academy of Management Journal*, 44(3), pp. 340-355.

Sabuncuoglu, I. and Karapinar, H.Y., 1999. Analysis of order review/release problems in production systems. *International Journal of Production Economics*, 63, pp. 259-279.

Scheinkopf, L.J., 2010. Thinking Processes Including S&T Trees. In*:* J.F. Cox, and J.G. Schleier, eds., *Theory of Constraints Handbook.* The United States of America: McGraw-Hill, 2010, pp. 729-786.

Scheinkopf, L.J., Kishira, Y., and Schragenheim, A., 2012. *Lineary High Touch Time: A New TOC Application*. TOCICO. [online]. Accessible at https://c.ymcdn.com/sites/www.tocico.org/resource/resmgr/2012_foundation_pdfs/scheinkopf-kishira-schragenh.pdf [Accessed 29th November 2018]

Scholz-Reiter, B., Windt, K. and Liu, H., 2011. Modelling dynamic bottlenecks in production networks. *International Journal of Computer Integrated Manufacturing*, 24(5), pp. 391-404.

Schmenner, R.W. and Swink, M.L., 1998. On theory in operations management. *Journal of Operations Management*, 17 (1), pp. 97-113.

Schragenheim, E., 2010. From DBR to Simplified-DBR for Make-to-Order. In: Cox, J. F. and Schleier, J. G., eds., *Theory of Constraints Handbook*. United States of America: McGraw Hill, 2010, pp. 211-238.

Schragenheim, E., Dettmer, H.W. and Patterson, J.W., 2009. *Supply chain management at warp speed: Integrating the system from end to end*. CRC Press, Boca Raton, FL.

Schragenheim, E., and Dettmer, H.W., 2000. *Manufacturing at Warp Speed: Optimizing Supply Chain Business Performance*. Boca Raton, FL: St. Lucie Press.

Schragenheim, E. and Ronen, B., 1991. Buffer Management: A Diagnostic Tool For Production Control. *Production and Inventory Management Journal*, 32(2), pp. 74-79.

Schragenheim, E. and Ronen, B., 1990. Drum-Buffer-Rope Shop Floor Control, *Production and Inventory Management Journal*, 31(3), pp. 18 – 23.

Seidler-de alvis, R. and Hartmann, E., 2008. The Use of Tacit Knowledge Within Innovative Companies: Knowledge Management in Innovative Enterprises. *Journal of Knowledge Management*, 12, pp. 133-147.

Shani, A.B., Coghlan, D. and Cirella, S., 2012. Action Research and Collaborative Management Research: More than Meets the Eye? *International Journal of Action Research,* 8 (1), 45-67.

Shani, A.B., and Pasmore, W.A., 2010. Organization Inquiry: Towards a New Model of the Action Research Process. In*:* D. Coghlan, and A.B. Shani, eds., *Fundamentals of Organization Development.* Los Angeles: Sage, 2010, pp. 249-259.

Shim, J.P., Warkentin, M., Courtney, J.F., Power, D.J., Sharda, R., and Carlsson, C., 2002. Past, present and future of decision support technology. *Decision Sypport Systems*, 33, pp. 111-126.

Simatupang, T.M., 2000. *Utilisation of buffer management to build focused productive maintenance.* Working paper. New Zealand: Massey University.

Simsit, Z. T., Gunay, N. S., Vayvay, O., 2014. Theory of Constraints: A Literature Review. *Procedia – Social and Behavioural Sciences*, 150, pp. 930-936.

Skinner, W., 2007. Manufacturing Strategy: The Story of its Evolution. *Journal of Operations Management,* 25, pp. 328-335.

Slomp, J., 2001. Human Factors in the Planning and Scheduling of Flexible Manufacturing Systems. In*:* MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling.* London: Taylor and Francis, 2001, pp. 179-197.

Smith, D., 2000. The measurement nightmare: how the theory of constraints can resolve conflicting strategies, policies, and measures. St. Lucie Press.

Sousa, R. and Voss, C.A., 2008. Contingency research in operations management practices. *Journal of Operations Management,* 26 (6), pp. 697 – 713.

Sousa, R. and Christopher, A., 2001. Quality management: Universal or context dependent? *Production and Operations Management*, 10 (4), pp. 383-404.

Spearman, M.L., 1997. On the Theory of Constraints and The Goal System. *Production and Operations Management*, 6(1), pp. 28-33.

Srikanth, M. (2010), DBR, Buffer Management, and VATI Flow Classification. In: Cox, J. F. and Schleier, J. G., eds., *Theory of Constraints Handbook*. United States of America: McGraw Hill, 2010, pp. 175-210.

Stevenson, M., 2006. BRIDGING THE GAP: Refining a Workload Control Concept for Practical Implementation. Ph.D. thesis, Lancaster University

Stevenson, M., 2006a. Refining a Workload Control (WLC) concept: a case study. *International Journal of Production Research*, 44(4), pp. 767-790.

Stevenson, M., Huang, Y., Hendry, L. and Soepenberg, E., 2011. The theory and practice of workload control: a research agenda and implementation strategy. *International Journal of Production Economics*, 131, pp. 689-700.

Stevenson, M., and Hendry, L., 2006. Aggregate load-oriented workload control: A review and a re-classification of a key approach. *International Journal of Production Economics*, 104, pp. 676-693.

Stevenson, M., Hendry, L.C., and Kingsman, B.G. (2005), A review of production planning and control: the applicability of key concepts to the make-to-order industry. *International Journal of Production Research*, 43(5), pp. 869-898.

Stratton, R., 2012. Variation and uncertainty buffering: a grocery supply case. *Supply Chain Management: An International Journal*, 17(6), pp. 655 – 665.

Stratton, R., and Knight, A., 2010. Managing Patient Flow using Time Buffers. *Journal of Manufacturing Technology Management*, 21(4), pp. 484 – 498.

Stratton, R., Robey, D., and Allison, I., 2008. Utilising Buffer Management to manage uncertainty and focus improvement. *In*: Proceedings of the International Annual Conference of EurOMA, Groningen, Netherlands.

Strohhecker, J., Hamann, M. and Thun, H., 2016. Loading and sequencing heuristics for job scheduling on two unrelated parallel machines with long, sequence-dependent set-up times. *International Journal of Production Research*, 54(22), pp. 6747-6767.

Susman, G.I., and Evered, R.D., 1978. An Assessment of the Scientific Merits of Action Research. *Administrative Science Quarterly*, 23 (4), pp. 582 – 603.

Tarafdar, M. and Gordon, S.R., 2007. Understanding the influence of information systems competencies on process innovation: A resource-based view. *Journal of Strategic Information System,* 16, pp. 353 – 392.

Tatsiopoulos, I.P., 1997. An Orders Release reference model as a link between production management and shop floor control software. *Computers in Industry,* 33, pp. 335 – 344.

Tatsiopoulos, I.P., and Kingsman, B.G., 1983. Lead time management. *European Journal of Operational Research,* 4, pp. 351 – 358.

Tenhiala, A., 2011. Contingency theory of capacity planning: The link between process types and planning methods. *Journal of Operations Management*, 29, pp. 65-77.

Thorpe, R., Anderson, L., Stewart, J. and Gold, J., 2015. The DBA and the Move to Professional Doctorates in Business and Management. In: L. Anderson, J. Gold, J. Steward and R. Thorpe, eds., *A Guide to Professional Doctorates in Business & Management.* Sage, 2015, pp. 1-16.

Thurer, M., Land, M.J., Stevenson, M., and Fredendall, L. D., 2017a. On the integration of due date setting and order release order. *Production Planning & Control*, 28(5), 420 - 430.

Thurer, M., Stevenson, M., Silva, C., and Qu, T., 2017b. Drum-buffer-rope and workload control in High-variety flow and job shops with bottlenecks: An assessment by simulation. *International Journal of Production Economics*, 188, pp. 116 – 127.

Thurer, M., Stevenson, M., and Land, M.J., 2016. On the integration of input and output control: Workload Control order release. *International Journal of Production Economics*, 174, pp. 43-53.

Thurer, M., Stevenson, M., Silva, C., Land, M.J., and Fredendall, L. D., 2012. Workload Control and Order Release: A Lean Solution for Make-To-Order Companies. *Production and Operations Management,* 21(5), pp. 939-953.

Thurer, M., Stevenson, M., and Silva, C., 2011. Three decades of workload control research: a systematic review of the literature. *International Journal of Production Research,* 49(23), pp. 6905-6935.

Thurer, M., Silva, C., and Stevenson, M., 2010. Workload control release mechanisms: from practice back to theory building. *International Journal of Production Research*, 48(12), pp. 3593-3617.

Torbert, W., 1998. Developing wisdom and courage in organizing and sciencing, *In:* Srivastva, S. and Cooperrider, D.L. (eds.), *Organizational Wisdom and Executive Courage*. San Francisco: Lexington Press, pp. 222-253.

Usher, R., 2002. A Diversity Of Doctorates: Fitness for the knowledge economy? *Higher Education Research & Development,* 21 (2), pp. 143-153.

Van de Ven, A.H., 2007. *Engaged scholarship: a guide for organizational and social research.* Oxford; New York: Oxford; New York: Oxford University Press.

Van Wezel, W., Cegarra, J., and Hoc, J., 2011. Allocating Functions to Human and Algorithm in Scheduling. In: Fransoo, J.C., Wafler, T. and Wilson, J., eds., *Behavioural Operations in Planning and Scheduling*. Berlin: Springer, 2011, pp. 339-370.

Voss, C.A., 2005. Alternative paradigms for manufacturing strategy. *International Journal of Operations & Production Management,* 25 (12), pp. 1211-1222.

Voss, C.A., 1995. Operations Management- from Taylor to Toyota- and Beyond? *British Journal of Management,* 6, pp. 17-19.

Watson, K. J., Blackstone, J. H., Gardiner, S. C., 2007. The evolution of a management philosophy: The theory of constraints, *Journal of Operations Management*, 25, pp. 387-402.

Westbrook, R., 1995. Action research: a new paradigm for research in production and operations management. *International of Operation & Production Management,* 15 (12), 6-20.

Whitehead, D., 2005. Project Management and Action Research: Two Sides of the Same Coin? *Journal of Health Organization and Management,* 19 (6), 519-531.

Wiendahl, H. P., 1995. *Load oriented manufacturing control*. Berlin Heidelberg, New York: Springer Verlah.

Wiendahl, H., Cieminski, G. and Wiendahl, H., 2005. Stumbling blocks of PPC: Towards the holistic configuration of PPC systems, *Production Planning & Control*, 16(7), pp. 634 – 651.

Wiers, V.C.S., 2001. Design of a Knowledge-based Scheduling System for a Sheet Material Manufacturer, In: MacCarthy, B.L. and Wilson, J.R., eds., *Human Performance in Planning and Scheduling.* London: Taylor and Francis, 2001, pp. 201 – 215.

Wiers, V.C.S., 1997. A Review of the Applicability of OR and AI Scheduling Techniques in Practice, *International Journal of Management Science,* 25(2), pp. 145 – 153.

Wiers, V.C.S. and van de Schaaf, T.W., 1997. A framework for decision support in production scheduling tasks, *Production Planning and Control*, 8(6), pp. 533-544.

Wight, O., 1970. Input/Output Control A Real Handle On Lead Time, *Production and Inventory Management*, pp. 9 – 31

Wilson, J.R., 2003. Support of opportunities for shopfloor involvement through information and communication technologies, *AI & Society*, 17(2), pp. 114-133.

Womack, J.P., Jones, D.T. and Roos, D., 1990. *The Machine That Changed The World.* The United States of America: Rawson Associates Scribner.

Wortmann, J., 1992. Production management systems for one-of-a-kind products. *Computers in Industry*, 19(1), pp. 79-88.

Zuber-Skerritt, O. and Perry, C., 2002. Action research within organizations and university thesis writing. *The Learning Organization,* 9 (4), 171-179.

Appendix 1

Innovate UK

Our ref: KTP009898

Dr Roy Stratton
Nottingham Trent University
Nottingham Business School
Victoria House
Burton Street
Nottingham
NG1 4BU

16 July 2018

Dear Dr Stratton

Nottingham Trent University and Amberol Limited

As you may be aware, the final report for each Knowledge Transfer Partnership is reviewed and graded by a panel of independent Assessors. The range of possible grades is ‘outstanding’, ‘very good’, ‘good’, ‘satisfactory’ and ‘unsatisfactory’.

I am pleased to inform you that your Partnership has been graded ‘Very Good’. I would like to congratulate all those involved in the Partnership in achieving this outcome and to thank you and your colleagues for your contribution to this success.

You may also like to be aware that the Project will be added to the short list from which KTP Case studies will be developed. We aim to maintain around 250 case studies covering the range of subject areas covered by Knowledge Transfer Partnerships.

Yours sincerely

Julia Bottomley
Post-Award Team

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Appendix 2

Appendix 6: Doctor of Business Administration (DBA): Ethical Approval Process, Principles & Guidelines.

Professional Doctorate Courses
Ethical Approval Checklist

An Ethical Approval Checklist must signed off by the research student, one member of the supervisory team, and a course leader, to signify that the proposed research conforms with good ethical principles and standards, before commencing any research in preparation for Document 4 within the Doctor of Business Administration course.

Assurance that all research will conform with good ethical standards is provided by the student when signing this form. Please complete this document following the DBA course ethical approval guidelines.

Award title	Doctor of Business Administration (DBA)
Cohort	17
Research Student's Name	AQUILA YEONG
Project title	Develop Strategic Organisational Growth through TOC Applications: An Action Research on a KTP case company.
Supervisors (List Lead supervisor first)	1. ROY STRATTON 2. EHSAN SABET 3. KEVIN LEE
Date	6/1/2016
Identify any questions in the completed form which indicate that approval by PDREC is required.	

At the end of each section it is indicated whether ethical approval must be sought from the Professional Doctorates Research Ethics Committee (PDREC).

1. Research Student

Section OA I: Familiarisation with policy

Please confirm if you are fully acquainted with policy guiding ethical research:

• NTU research ethics policy, and the procedures for ethical approval on professional doctorate courses	[✓ Yes]	~~No~~
• The guidelines for ethical research promulgated by a professional association, as appropriate	[✓ Yes]	~~No~~
• The Regulations for the Use of Computers (*see* NTU website)	[✓ Yes]	~~No~~
• Guidelines for Risk Assessment in Research (Appendix 7)	[✓ Yes]	~~No~~

If you answered **NO** to any of these questions, please note that you must study these guidelines and regulations before proceeding to complete the remainder of this form.

Section OA II: External Ethical Review

OB.1 Has a favourable ethical opinion been given for this project by an NHS or social care research ethics committee, or by any other external research ethics committee? An external research ethics committee means any research committee *other* than the PDREC at Nottingham Trent University. Submission of this form is *not* a submission to an external research ethics committee.	~~Yes~~	[✓ No]
OB.2 Will this project be submitted for ethical approval to an NHS or social care committee or to any other external research ethics committee? An external research ethics committee means any research committee *other* than the PDREC at Nottingham Trent University. Submission of this form is *not* a submission to an external research ethics committee.	~~Yes~~	[✓ No]

If you answered **YES** to either of these two questions, please sign the declaration at the end of the form and submit it (together with a letter confirming ethical approval from the external committee) before starting any research.

If you answered **NO** to both questions, please proceed to Section A

Section A: Investigators

A.1. Have you attended the professional doctorate workshops on research methods or attended other award-bearing or training courses on research methods?	[✓ YES]	~~NO~~
A.2. Are you in regular contact with your supervisory team?	[✓ YES]	~~NO~~
A.3. Can you confirm that you are **NOT** expecting to undertake physically invasive procedures (not covered by a generic protocol) during the course of the research?	[✓ YES]	~~NO~~
A.4 Can you confirm that you will **NOT** be in a position of authority that may compromise the integrity of participants (e.g. a member of academic staff using his/her students, or a manager using subordinates as participants)?	[✓ YES]	~~NO~~

If you have answered **NO** to question C.1, because you are not undertaking empirical work, proceed to the declaration at the end of this form. If you have answered **NO** to question C.2, an application for ethical approval needs to be made to the PDREC.

Section D: Consent and Deception

Informed Consent & Data Withdrawal

D.1 Will participants, or the appropriate authority, be fully informed of the objectives, and of all other particulars of the investigation (preferably at the start of the study, but where this would interfere with the study, at the end)?	[✓ Yes]	~~No~~
D.2 Will participants, or the appropriate authority, be fully informed of the use of the data collected (including, where applicable, ownership of any intellectual property arising from the research)?	[✓ Yes]	~~No~~
D.3 For detained persons, members of the armed forces, employees, students and other persons who may not be in a position to give fully independent consent, will care be taken over the gaining of freely informed consent?	[✓ Yes]	~~No~~
D.4 Will participants, or the appropriate authority, be informed of their right to withdraw from the investigation at any time (or before a specific deadline) and to require their own data to be destroyed?	[✓ Yes]	~~No~~

If you have answered **NO** to any of questions D.1-D.4, an application for ethical approval needs to be made to the PDREC.

D.5 Does the study involve deception of participants (i.e., withholding of information and/or misleading participants) which could potentially harm and/or exploit participants?	~~Yes~~	[✓ No]

If you answer **NO** to question D.5, please proceed to section E.

Deception

D.6 Is deception an unavoidable part of the study?	Yes	No
D.7 Will participants, or the appropriate authority, be de-briefed and the true object of the research revealed at the earliest stage upon completion of the study?	Yes	No
D.8 Has consideration been given to the way that participants, or the appropriate authority, will react to the withholding of information or deliberate deception?	Yes	No

If you have answered **NO** to questions D.6-D.8 an application for ethical approval needs to be made to the PDREC.

If you answered **NO** to any of questions A.1-A.4, an application for ethical approval needs to be made to the PDREC.

Section B: Participants & Method/Procedures

B.1 Does the research involve vulnerable participants? If **not**, go to Section C

B.2 If the research does involve vulnerable participants: will participants knowingly be recruited from one or more of the following vulnerable groups?

• Children under 18 years of age	Yes	No
• People over 65 years of age who are perceived to be vulnerable	Yes	No
• Pregnant women	Yes	No
• People with mental illness	Yes	No
• Prisoners/detained persons	Yes	No
• Other vulnerable group	Yes	No

- please specify: ______________________________

B.3 Have you been asked to obtain a Disclosure and Barring Service (DBS) check as a condition of access to any source of data in the UK for this document?	Yes	No

B.4 To the best of your knowledge, please indicate whether the proposed study:

• Involves procedures likely to cause physical, psychological, social or emotional distress to participants	Yes	No
• Is designed to be challenging physically or psychologically in any way (includes any study involving physical exercise)	Yes	No
• Exposes participants to risks or distress greater than those encountered in their normal daily life	Yes	No
• Involves the use of hazardous materials	Yes	No

If you have answered **YES** to any of questions B.1-B.4, an application for ethical approval needs to be made to the PDREC.

Section C: Observation/Recording

C.1 Does the study involve data collection, (including but not limited to the observation or recording of participants)? Note that data collection includes the re-use of material originally collected for a non-research purpose (e.g. client or student data already in your possession).	[✓ Yes]	~~No~~
C.2 Will those contributing to the data collected or the appropriate authority, be informed that the data collection will take place?	[✓ Yes]	~~No~~

Section E: Storage of Data and Confidentiality

Please see University guidance on https://www.ntu.ac.uk/intranet/policies/legal_services/data_protection/16231gp.html. If you are a member of NTU staff you can obtain direct access to this with your staff username and password. If you are not a member of NTU staff, please request of copy from your supervisor or course leader.

E.1 Will all information on participants be treated as confidential and not identifiable unless agreed otherwise in advance, and subject to the requirements of the law of the relevant jurisdiction?	[✓ Yes]	~~No~~
E.2 Will storage of data comply with the Data Protection Act 1998 and the law of any non-UK jurisdiction in which research is carried out?	[✓ Yes]	~~No~~
E.3 Will any video/audio recording of participants be kept in a secure place and not released for use by third parties?	[✓ Yes]	~~No~~
E.4 Will video/audio recordings be destroyed within six years of the completion of the investigation?	[✓ Yes]	~~No~~

If you have answered **NO** to questions E.1-E.4, an application for ethical approval needs to be made to the PDREC.

Section F: Incentives

F.1. Have incentives (other than those contractually agreed, salaries or basic expenses) been offered to you by any funder of the research to conduct the investigation?	~~Yes~~	[✓ No]
F.2. Will incentives (other than basic expenses) be offered to potential participants, or the appropriate authority, as an inducement to participate in the investigation?	~~Yes~~	[✓ No]

If you have answered **YES** to questions F.1-F.2, an application for ethical approval needs to be made to the PDREC.

The design of the participant information sheet/consent form and of any research instrument (including questionnaires, sampling and interview schedules) that will be used, have been discussed with my supervisor(s).	[✓ Yes]	~~No~~

Compliance with Ethical Principles

Please sign the declaration below, to confirm that this form has been completed to the best of your knowledge and after discussing the answers provided with your supervisor(s). If at any stage you have been asked to submit an application for ethical approval to the PDREC please also complete and submit the appropriate form.

Signature of Research Student .... Date 6/1/2016

Signature of Lead Supervisor .... Date 6/1/2016

Signature of Course Leader DJKirk .... Date 13/1/2016