Determining the most appropriate Production Planning and Control system for Small Enterprises: framework and field tests

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Nederlandse samenvatting

De productiebedrijven vandaag werken in een zeer competitieve omgeving, gekenmerkt door onzekerheid omtrent de vraag en toenemende klanteneisen. Productie Planning en -Controle systemen (PPC) zijn belangrijke instrumenten die bedrijven toelaten om hun productieprocessen op te lijnen met deze volatiele omgeving (Olhager en Rudberg, 2002). De selectie van de juiste PPC is evenwel een moeilijke beslissing, omwille van de talrijke opties die de markt aanbiedt, soms voorgesteld als universele oplossingen. Daarom hebben verschillende auteurs de noodzaak gesuggereerd om de principes van een Productie Planning en -Controle systeem kritisch af te zetten tegenover de kenmerken van het bedrijf waar het systeem zou gebruikt worden. Eén van deze auteurs (Tenhiala 2011) stelt dat het wellicht voordelig zou zijn om voorbije implementaties van de PPC te onderzoeken, de geschiktheid van de geselecteerde Productie Planning en -Controle systemen en de grenzen van hun toepasbaarheid. Ook de relatie tussen de PPC kenmerken en de markt- en productiestrategie van het bedrijf heeft zijn belang (Olhager en Rudberg, 2002), zeker als men de gevolgen beschouwd wanneer er een mismatch optreedt tussen beide. Sommige auteurs (Stevenson, Hendry and Kingsman, 2005) suggereren zelfs dat de operationele performantie van bedrijven kan lijden indien de PPC niet geschikt is voor de markt- en productiestrategie die ze moet ondersteunen. De reden voor deze kritische gevolgen is te zoeken in de hoge mate waarin een PPC geïntegreerd is met de functionele domeinen van een bedrijf (MacCarthy en Fernandes, 2000), en zijn opmerkelijke impact op sleutelindicatoren zoals onderhanden werk (WIP), doorlooptijden (lead time) en leverbetrouwbaarheid (DDP). Deze negatieve gevolgen zijn nog kritischer voor kleine en middelgrote bedrijven (KMO). Beperkte financiële middelen en onvoldoende concurrentiekracht tegenover grote wereldwijde bedrijven maken KMO’s veel gevoeliger voor de negatieve gevolgen van een verkeerde PPC keuze(Ahmad en Qiu, 2009) (Dean, Tu en Xue, 2009). Stevenson et al (2005) verklaren dit op basis van de beperkte financiële draagkracht van deze categorie bedrijven. Als gevolg hiervan is het nodig om PPC alternatieven te identificeren die coherent zijn met specifieke kenmerken van KMO’s, zoals beperkte toegang tot financiële middelen (Stevenson et al, 2005), een gebrek aan gesofisticeerde informatiesystemen (Kagan, Lau en Nusgart, 1990) en een sterke focus op het nastreven van korte termijn opportuniteiten in plaats van lange termijn performantie (Towers en Burnes, 2008).

Het huidig onderzoek focust op het identificeren van de beste Productie Planning en -Controle systemen voor KMO’s. Gebruik makend van bestaande raamwerken voor de selectie van Productie Planning en -Controle systemen, heeft ons onderzoek een aantal dimensies opgesteld waarmee bedrijven kunnen worden gecategoriseerd volgens kenmerken relevant voor de PPC selectie. Een duidelijke categorisering van het bedrijf is een eerste stap in de methode. Vervolgens wordt voor elke markt, product en proces dimensie de typische aanpak van elke PPC geëvalueerd op een niet-lineaire schaal. De geschiktheid van elk Productie Planning en -Controle systeem kan dan worden bepaald op basis van het niveau van contributie of afwijking die de principes en mechanismen van de PPC levert ten opzichte van de kenmerken van het bedrijf.

De methode werd vervolgens gevalideerd op basis van de 5 meest gebruikte PPC mechanismen uit de literatuur, en ook ten opzichte van de kenmerken van KMO’s uit Ecuador, geselecteerd als representatief voor deze doelgroep.

De geëvalueerde systemen zijn: MRP (Material Requirements Planning), Kanban (kaartgestuurd pull systeem), WLC (Workload Control), DBR (Drum-Buffer-Rope) en S-DBR

(Simplified DBR). Volgens onze verwachtingen haalden de PPC systemen die meer georiënteerd zijn naar Make To Order omgevingen (zoals WLC, DBR en S-DBR) betere scores dan de andere methodes die meer geschikt zijn voor repetitieve omgevingen (zoals MRP en Kanban). Onder deze beschikte S-DBR over de nodige kenmerken die zorgden voor de hoogste score. S-DBR blijkt dus het meest geschikt als Productie Planning en -Controle systeem voor Ecuadoriaanse KMO's. Kenmerken zoals eenvoud door het gebruik van maar één beschermingsbuffer en productieplanning zonder gedetailleerde bottleneckroostering maken van S-DBR een meer toegankelijke methode voor die omgevingen waar men geen grote hoeveelheden informatie kan verwerken. Dit betekent dat bij S-DBR het niet nodig is om te beschikken over gesofisticeerde IT systemen of hooggeschoolde arbeid. Tenslotte is S-DBR ontworpen om MTO omgevingen te besturen. S-DBR concepten zoals geplande bezetting en bufferbeheer maken het zeer geschikt voor bedrijven die een hoge Due Date Performance (leverbetrouwbaarheid) nastreven.

Een ander belangrijk onderzoeksresultaat was een duidelijke lijst van sterktes en zwaktes ten opzichte van KMO's voor elk van de 5 onderzochte systeemtypes. Op basis van dit raamwerk kan een KMO die een Productie Planning en -Controle systeem wenst te kiezen meer gericht afstemmen met zijn eigen kenmerken. Bovendien kan dezelfde lijst dienen als inspiratie om toekomstige Productie Planning en -Controle systemen te ontwikkelen die beter afgestemd zijn op de KMO noden. Teneinde empirische bewijzen te verzamelen dat het raamwerk wel degelijk bruikbaar en nuttig is werd in 4 KMO's een diepgaand case onderzoek uitgevoerd. In elk van de 4 studies werden aanzienlijke verbeteringen genoteerd in de operationele maatstaven zoals servicegraad, doorlooptijd en throughput (totale omzet gemeten volgens de principes van Constraint Theory), door toepassing van S-DBR. De studies toonden ook aan dat de operationele kenmerken van het bedrijf een wezenlijke invloed hebben op de implementatie van Productie

Planning en -Controle systemen en op de behaalde resultaten. Tenslotte werden tijdens de studie ook opportuniteiten tot verbetering van het S-DBR implementatieproces ontdekt, en werden bijkomende onderwerpen voor toekomstig onderzoek geïdentificeerd.

Deze onderwerpen zijn: (a) het effect onderzoeken van alternatieve dispatching technieken in combinatie met S-DBR; (b) de toepasbaarheid onderzoeken van alternatieve methodes, zoals controlekaarten, om de leverbetrouwbaarheid van het bedrijf op te volgen (DDP); (c) het mechanisme van Lee et al (2010) verifiëren om de leverdata vast te leggen wanneer de bottleneck (CCR) niet in het midden van de processequentie is gelegen; (d) de toepasbaarheid onderzoeken van alternatieve mechanismen zoals visuele tools die in ware tijd informatie verstrekken over de accuraatheid van de procestijden op de bottleneck (CCR); (e) analyseren van de operationele impact van het verhogen van de (over)capaciteit op niet-bottleneck stations in omgevingen waar het technisch of financieel niet haalbaar is om de focus exclusief te leggen op de bottleneck zelf.

Deze studie opent dus nieuwe perspectieven om een nood te lenigen die reeds vele decennia bestaat: een Productie Planning en -Controle systeem aangepast voor KMO’s in een MTO omgeving.

English Summary

Today, manufacturing companies operate in a highly competitive climate characterized by uncertainties related to demand and increasing customer expectations. Production planning and control systems (PPCs) are very important tools that allow companies to align their manufacturing processes within this highly variable environment (Olhager & Rudberg, 2002). However, the selection of a PPCs is not an easy decision resulted of the multiple options offered at the market that in some cases are presented as universal solutions. In this way, several authors have suggested the critical of contrasting the principles of the PPCs to the characteristics of the company where probably it will be applied. One of these authors is Tenhiala (2011)) that considers beneficial exploring previous implementation, the suitability of the selected PPCs and determine the expecting limitations of its applicability. Similarly, Olhager and Rudberg (2002)) insist on the importance of the relationship between the characteristics of the PPCs and the market and manufacturing strategy presenting the consequences of a substantial mismatch among them. This aim is consistent with the proposed by Stevenson*, Hendry, and Kingsman† (2005)) who suggest the negative impact on the operational performance associated to select a PPCs not suitable to the market and manufacturing strategy of the company. The critical consequences presented by the authors can be explained by the highly integrative character of PPCs with other functional areas on the company (B. L. MacCarthy & Fernandes, 2000) and its notably impact with key operational measures such as Work in process, lead times or due date performance (B. L. MacCarthy & Fernandes, 2000).

Despite previous literature presents the negative branches resulted of not using a suitable PPCs the consequences are still more critical for the small and medium enterprises (SMEs). Characteristics such as the financial resource limitations or the lack of leverage to face tough

competition from large global manufacturers (Ahmad & Qiu, 2009) (Dean, Tu, & Xue, 2009) make of SMEs highly susceptible to suffering the consequences of a wrong decisions with respect to the selection of the PPCs. The SMEs are especially susceptible to suffering the consequences of this type of decisions. Stevenson* et al. (2005) explains it based on the financial resource limitations proper of this type of industries. Consequently, it is necessary to find out PPCs alternatives aligned with the SMEs peculiarities such as a limited access to financial resources (Stevenson* et al., 2005), a lack of sophisticated information systems (Kagan, Lau, & Nusgart, 1990) or a strong focus in maximizing short term opportunities rather than achieving an optimized long term performance (Towers & Burnes, 2008).

Thus the present research focuses primary in determining the most appropriate Production planning and control system for the Small and Medium enterprises. For that based on previously proposed frameworks for the selection or design of PPCs our research establishes a group of dimensions used to categorize the company where the PPCs will be applied. Taking a clear categorization of the company is the first step to determine the suitability of the PPCs. Secondly for each of the market, product and process dimensions the PPCs approaches are evaluated using a non-linear scale. The suitability of a PPCs depend on the level of contribution or inconsistency between the characteristics of the company and the principles or mechanism of the PPCs.

At this research our proposed framework was evaluated considering five of the most classic PPCs approaches found in the literate and evaluated with respect to the characteristics of the Ecuadorian SMEs. The Ecuadorian SMEs were selected considering present similar characteristics to the identified at the majority of the SMEs.

MRP, Kanban, Workload Control (WLC), Drum-Buffer- Rope (DBR) and Simplified DBR were the PPC systems evaluated. According to our expectations the PPC systems oriented to MTO environments such as WLC, DBR and S-DBR obtained greater punctuations than the other approaches more suitable to repetitiveness environments such as MRP and Kanban. Among them S-DBR presented the necessary features that influence positively in achieving the highest score appearing as the PPCs more suitable to the Ecuadorian SMEs characteristics. Characteristics such as its simplicity resulted of maintaining just one protection buffer and manage the production without a detailed CCR scheduling make of S-DBR more accessible to environments where processing a high volume of information is infeasible. Consequently in a S-DBR implementation the inclusion of sophisticated IT systems or the requirement of highly skilled labour is not indispensable. Finally S-DBR is a system designed for the managing of MTO environments. The inclusion of concepts such as the planned load or the buffer management make S-DBR highly recommended for companies that pursue high DDP.

It is notorious that additional to establish S-DBR as the most suitable PPCs our framework allowed to determine the strengths and weakness of the evaluated PPCs for each of the framework’s dimensions. This characteristic make of our framework not only a tool for the selection but additionally for the design considering its capacity for suggesting the mechanisms of each PPCs that in combination can generate a highly suitable PPCs for a specify production environment. In order to obtain empirical evidence that validate the results of the framework a case study research was developed presenting the implementation of S-DBR in four SMEs. At all of the cases significant improvements were presented in operational measures such as service level, lead time, or throughput. Additionally, the real application of S-DBR presented how the operational characteristics of the company influence on the implementation processes and its influence in the performance measures.

Finally improvement opportunities in the S-DBR implementation process were identified and suggested as proposal enhancements that could be evaluated at a future research. The improvement opportunities include evaluating different release techniques in combination with S-DBR principles. Exploring the applicability of alternative methodologies such as control charts that allow monitor the company’s due date performance (DDP). Verify the effectiveness of the mechanism proposed by Lee et al. (2010) to determine the due date commitments when the CCR is not located at the middle of the routing. Exploring the application of alternative mechanisms such as visual tools that could offer on real time the required information with respect to the accuracy of the processing time estimations on the CCR. Analysing the operational impact of expanding the capacity at non-constrained workstations in environments where focus exclusively in the capacity constrained resource (CCR) is infeasible technically or financially.

1

Introduction

This chapter presents the foundation of this research, the research questions and the applied methodology presented alongside this document.

1.1 Introduction

At present, manufacturing companies have to cope with a highly competitive climate characterised by uncertainties related to varying demands and increasing customer expectations. In this respect, production planning and control systems (PPCs) are critical tools, that allow companies to align their manufacturing processes with this highly variable environment (Olhager & Rudberg, 2002). The notable impact of PPCs on key measures, such as work in process (WIP), lead times or due date performance (B. L. MacCarthy & Fernandes, 2000), make them well suited to support crucial competitive decisions (Gaury, Kleijnen, & Pierreval, 2001).

However, one of the primary concerns during PPC design selection is determining its applicability based on the company's characteristics. Several studies in the operations management literature have addressed this issue. For example, Tenhiala (2011) investigated the benefits for organisations exploring previous implementations, the suitability of the selected PPCs and the expected limitations of their applicability. Similarly, Olhager and Rudberg (2002) insisted on the importance of the relationship between the selected PPCs and the market and manufacturing strategy and presented the consequences of a substantial mismatch among them. This aim is consistent with the ideas of Stevenson* et al. (2005), who suggested that the detriment to operational performance measures is directly associated with the selection of a PPC that is not suitable for the market and the company's manufacturing strategy. The critical consequences presented by the authors can be explained by the highly integrative characteristics of PPCs with other functional areas in a company (B. L. MacCarthy & Fernandes, 2000).

Although improper PPC selection can substantially affect the operational performance of any company, Small and Medium Enterprises (SMEs) are especially susceptible to the negative consequences of such decisions. Stevenson* et al. (2005) attributed this characteristics of SMEs to the financial resource limitations of this type of firm. Consequently, it is necessary to find PPC alternatives that are aligned with the particular characteristics of SMEs, such as limited access to financial resources (Stevenson* et al., 2005), a lack of sophisticated information systems (Kagan et al., 1990) and a strong focus on maximising short-term opportunities rather than achieving optimised long-term performance (Towers & Burnes, 2008).

To bridge this gap, the present research analysed different proposed methodologies to assist in the choice or design of a PPC. The primary objective was the establishment of a framework to support the selection of PPCs suitable for the characteristics of SMEs. To evaluate our framework, we applied the method to identify a PPC suitable for Ecuadorian SMEs based on five classic PPC approaches: MRP, Kanban, workload control (WLC), drum-buffer-rope (DBR) and simplified DB. Ecuadorian SMEs were selected because their characteristics coincide with the general description offered in the literature for SMEs located throughout the world.

Among the various approaches, S-DBR was found to be the most suitable for the characteristics of Ecuadorian SMEs. This system is relatively simple due to the minimisation of planning and an increasing emphasis on the control of the execution (Schragenheim, Dettmer, & PATTERSON, 2009b). In this way, S-DBR changes the focus from the development of an optimal solution to provide the necessary flexibility to protect the system from operational variation and uncertainty. These characteristics make S-DBR an appropriate option for Ecuadorian SMEs because of the trade-off between flexibility and efficiency required in such firms (Van Wezel, Van Donk, & Gaalman, 2006).

The S-DBR concept has received some attention in the literature, particularly in theoretical studies that discuss its fundamentals (Schragenheim & Dettmer, 2000a; Schragenheim, Dettmer, & Patterson, 2009c) or that propose alternative procedures to enhance its performance in non-traditional environments (Y.-C. Chang & Huang, 2011; Jun-Huei Lee, Chang, Tsai, & Li, 2010; Souza & Pires, 2013). However, little research on S-DBR implementations has been conducted to determine its effectiveness in realistic operations. Thus, this thesis expects to contribute to the OM literature by offering a better understanding of the empirical relationships between SME characteristics and the design of the S-DBR implementation process. To demonstrate this aspect of the work, a case study was selected to investigate real cases of S-DBR implementation at four Ecuadorian SMEs.

Finally, this research is practical for practitioners because it serves as a guide for adapting S-DBR to companies with different characteristics. The recommendations include the adaption of mechanisms or tools selected from other methodologies that are expected to enhance S-DBR performance.

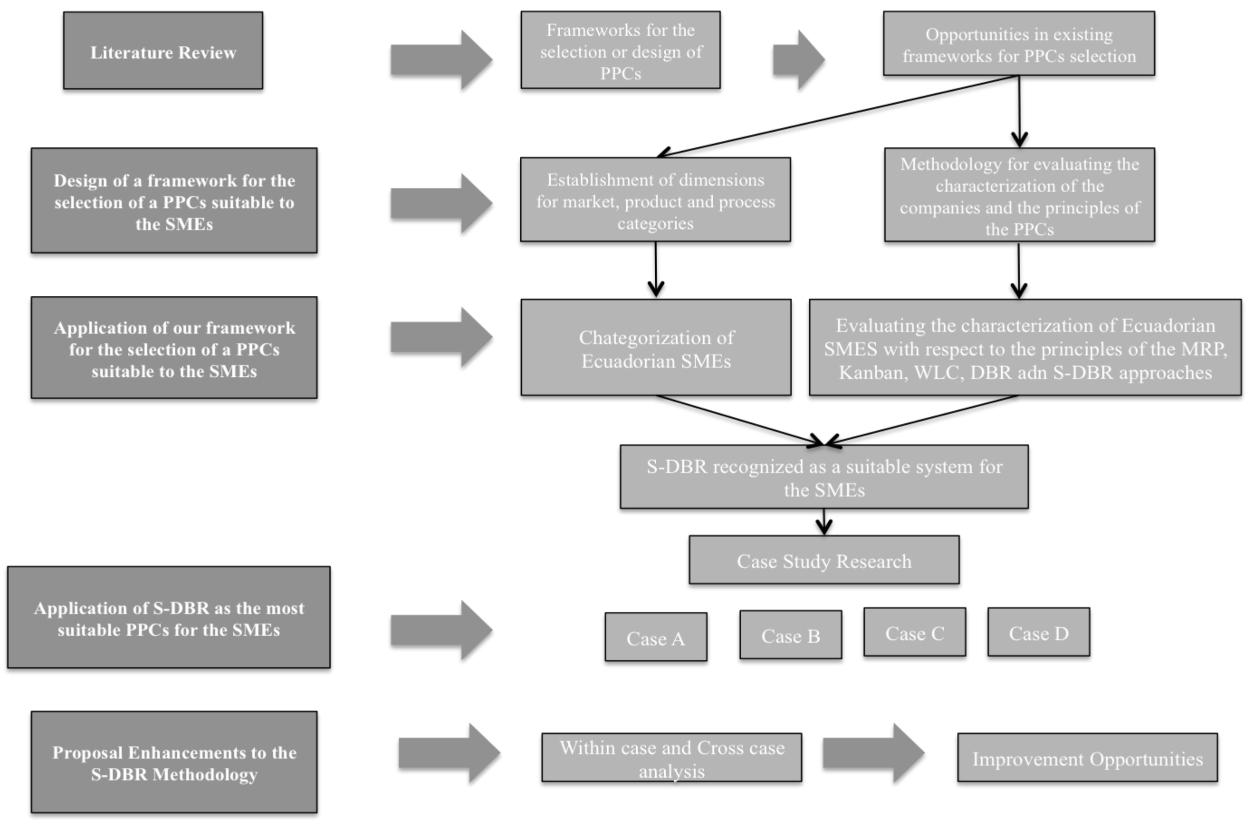
1.2 Research Questions

1. Which factors influence the selection of a PPC?
2. How are characterised SMEs in terms of critical aspects required for PPC selection?
3. Which PPC system is most suitable for the characteristics of SMEs?

1.3 Research Methodology

The research methodology used in this doctoral research is presented in figure 1.1. In chapter 2, a literature review of the previously proposed frameworks for PPC selection or design is presented. In addition, a brief description of each assessed PPC in terms of suitability for Ecuadorian SMEs is included in this chapter. In chapter 3, we propose a framework for the selection or design of PPCs, including a detailed description of each category and dimension. Finally, the framework is applied to select a suitable PPC based on the characteristics of Ecuadorian SMEs. Chapter 4 presents the application of a case study to validate the effectiveness of the previously selected PPC and identify potential opportunities for enhancing its performance. Within- and cross-case analyses were used to identify similarities and differences in the characteristics of the companies in which the PPCs were applied and their influence on company performance. Chapter 5 presents additional development of the proposals for each opportunity identified in the previous chapter. Finally, chapter 6 presents the conclusions of this research and the future implications of this work.

Figure 1.1: Graphical description of the research methodology



1.4 Contribution

This study offers three major contributions to the OM field related to production planning and control systems (PPCs). The first contribution is a framework aimed at PPC selection or design that includes qualitative and quantitative dimensions directly related to the operational principles of PPCs. Second, by applying our framework, this research provides a suitable analysis of five classic PPCs with respect to the common characteristics of SMEs. Finally, based on our case study, we offer a set of proposals for improving the performance of the previously selected PPCs.

2

Literature Review

This chapter presents a general review of the literature with respect to the previously proposed frameworks for PPC selection or design and discusses opportunities for future development.

2.1 A review of previously proposed PPCs selection frameworks

An important group of authors have presented production system classifications. One of the primary objectives of these classifications was to identify the characteristics of complex production systems to facilitate the identification of their correspondence to the properties of the different PPCs (B. L. MacCarthy & Fernandes, 2000). The first classifications, such as those proposed by Mallick and Gaudreau (1951), Burbidge (1978), Schmitt et al. (1985), Larsen and Alting (1993) and Wysk and Smith (1995), were primarily focused on operational aspects, with limited attention to such criteria as product characteristics or market requirements.

Later studies investigated the strong connection between these aspects and the design of PPCs. For example, Volmann et al. (1997b) reported the strong influence of market requirements and product features on PPC design. Similarly, Hill (2000) proposed the existence of a strong link between market requirements and manufacturing concerns. Olhager and Wikner (2000) considered that various dimensions, such as market qualifiers, order winners and product characteristics, significantly influence the design and operation of PPCs. Finally, Olhager and Rudberg (2002) concluded that PPC design involves a mixture of market, product and process issues.

Furthermore, some studies proposed frameworks for PPC selection that combine operational, market and product dimensions. For example, Hayes and Wheelwright (1984) and Silver et al. (1998) proposed a PPC classification that relates the process pattern with the extent of product mixing. MacCarthy and Fernandes (2000) presented an extensive classification that integrates process and product dimensions. Similarly, Vollmann et al. (2005) established a framework that simultaneously includes process and market requirements.

Other methodologies have been proposed specifically for designing a certain type of production system. For example, Gaury et al. (2001) proposed a methodology aimed at customising pull control systems. Similarly, Henrich et al. (2004) established a framework for exploring the applicability of the workload control (WLC) concept. Finally, Stevenson et al. (2005) reviewed the applicability of several PPC systems aimed specifically at the make-to-order (MTO) industry.

In other cases, the suggested frameworks are orientated toward PPC software packages. For example, Tatsiopoulos and Mekras (1999) presented a rule-based expert system that describes a production system typology and combines process and product parameters. Other studies used more contemporary techniques, such as Howard et al. (2000), who performed a case study of SMEs to increase the accuracy and usability of a rule-based system for the specification of PPCs.

2.2 Opportunities identified in existing frameworks for PPC selection

The previously developed frameworks and classifications have led to a better understanding of the true user requirements encountered during PPC design or selection. However, in most cases, the included characteristics are limited to a few dimensions or composed exclusively for qualitative categories.

For example, Hayes and Wheelwright (1984) and Silver et al. (1998) included only one product and one qualitative process dimension as part of their frameworks for categorising PPCs. In the framework proposed by Vollmann et al. (2005), although market, product and process characteristics are included, only a few qualitative dimensions of each category are considered in their approach. Their method is similar to the methodology proposed by Gaury et al. (2000), where, with the exception of some process characteristics, the market category is only represented by two dimensions, and the product category is completely excluded from the analysis. In the framework proposed by Henrich et al. (2004), although some quantitative dimensions are included, most of them are related to the process, with only a few related to the market. Tatsiopoulos and Mekras (1999) proposed an expert system in which the selection of PPCs applies a typology that uniquely includes product and process characteristics.

The proposal of Stevenson et al. (2005) is an exception; it is not a formal framework but a discussion that includes elements of the product, process and market requirements. Similarly, Howard et al. (2000) proposed a rule base that consists of 142 characteristics, 39 management concerns and 223 activities. This framework likely has the highest number of dimensions. However, its technological requirements greatly limit its application, especially for SMEs.

Based on this background, a framework is needed for use in this study. This framework must consider both quantitative and qualitative dimensions to evaluate the different PPCs using an operative approach.

3

Design and application of a framework for the selection of a PPCs suitable for the SMEs.

This chapter presents details of every dimension included in the proposed framework for PPC selection or design. Additionally, an example is presented to demonstrate the application of this framework to identify a suitable PPC system for Ecuadorian SMEs based on five classic PPC approaches.

3.1 Framework for the selection or design of a PPCs

The primary objective of PPCs is to ensure a match between the product requirements expressed on the master production schedule (MPS) and the available capacity (Henrich et al., 2004) in a way that allows the performance objectives to be met (Bonney, 2000).

Each manufacturing environment demands PPCs with specific characteristics that connect the functions of the companies in which they will be applied. Therefore, different approaches may be more suitable than others and should be evaluated in terms of how they meet the demands of the companies where they will be implemented.

Traditionally, the frameworks that determine the applicability of a PPC are based on contrasting the PPC's principles with a group of company dimensions expressed as market, process or product requirements. Depending on how well the principles fit the company, the PPC is considered well or poorly suited to the environment considered. Table 3.1 presents a review of the literature published since 1992. This table describes the different criteria applied in previous proposed frameworks to support the selection of PPCs

Table 3.1 Dimensions applied in previous frameworks for the PPCs selection

Criteria for supporting PPC selection	References
Product Characterisation	
Level of customisation	Berry and Hill (1992),Vollmann (1997), MacCarthy and Fernandes (2000), Stevenson et al. (2005)),
Product mix	Berry and Hill (1992), Vollmann (1997), Silver (1998), Stevenson et al. (2005)
Product structure	MacCarthy and Fernandes (2000)
Number of products	MacCarthy and Fernandes (2000)
Processing Characterisation	
Process pattern	Larsen and Alting (1993), Silver (1998),MacCarthy and Fernandes (2000) ,Henrich et al. (2004), Stevenson et al. (2005)
Releasing control	Stevenson et al. (2005)
Volume batch	Berry and Hill (1992), Vollmann (1997), MacCarthy and Fernandes (2000)
Type of layout	MacCarthy and Fernandes (2000)
Setup/Processing time ratio	Henrich et al. (2004)
Organisation control	Vollmann (1997), MacCarthy and Fernandes (2000)
Information requirements	Larsen and Alting (1993)
Planning capacity	Kingsman (1996)
Shop floor personnel criteria	Maurice Bonney (2000)
Processing time lumpiness	Henrich et al. (2004)
Processing time variability	Henrich et al. (2004)
Routing length	Henrich et al. (2004)
Routing flexibility	Henrich et al. (2004)
Level of convergence	MacCarthy and Fernandes (2000), Henrich et al. (2004)

Market Requirements

Due date planning requirements	Kingsman (1996),Olhager and Wikner (2000), Stevenson et al. (2005)
Order winner	Berry and Hill (1992), Larsen and Alting (1993),Stevenson et al. (2005)
Demand change. total volumen	Berry and Hill (1992), Larsen and Alting (1993),Vollmann (1997)
Demand changes. Product mix	Berry and Hill (1992), Larsen and Alting (1993),Vollmann (1997)
Speed on delivery	Vollmann (1997)
Schedule changes	Vollmann (1997)
Arrival intensity	Henrich et al. (2004)
Interval arrival time variability	Henrich et al. (2004)
Due date tightness	Henrich et al. (2004)
Variability of due date allowances	Henrich et al. (2004)

Our framework is elaborated by combining the market, product and process dimensions listed in the Table 3.1. Like other frameworks, our framework still maintains a subjective component; however, a quantitative approach is reserved for dimensions for which offering an excessively general or very superficial characterisation could negatively influence the selection. This study is expected to offer a proper balance between the level of detail and the level of aggregation for each of the selected dimensions.

The framework is applied in two phases. The first is the characterisation of the company considering the dimensions proposed by the framework. Thereafter, the possible PPCs are evaluated by determining which PPC provides the best fit to the description of the company for each characteristic included in the framework. For this purpose, a non-linear scale presented in Table 3.2 is applied, which gives each dimension a positive or negative score depending on the positive or negative relationship between the characteristic of the company and the principles of the PPC.

Table 3.2: Scale for evaluating the potential relationships between the characteristics of the company and the principles of PPCs.

Score	Categorization	Description
9	Highly positive correlation	The PPC's principles fit perfectly to a company's characteristics and significantly influence the achievement of its goals.
3	Some positive correlation	The PPC's principles are in accordance with a company's characteristics and support the achievement of its goals.
1	Neutral	The PPC's principles are not in conflict with a characteristics of the company and do not affect the achievement of its goals.
-3	Some negative correlation	The PPC's principles are not suitable for a company's characteristics and negatively influence the achievement of its goals.
-9	Highly negative correlation	PPC's principles are opposite to a company's characteristics and significantly jeopardise the achievement of its goals.

The suitability of a PPC for a company is based on how the numerous characteristics of the firm support the principles of the PPC. A description of each dimension and the reasons for its selection is presented in the following sections

3.1.1 Product Characterization

Product characteristics have been cited in previous studies as an important input to manufacturing strategy and an influential category in the design of PPCs (Johnson & Montgomery, 1974) (Hill, 2000) (B. L. MacCarthy & Fernandes, 2000) (Olhager & Rudberg, 2002). Product issues, such as volume or product mix, have been the most widely discussed issues in previous studies. In fact, frameworks such as that presented by Silver (1998) use a combination of volume and product standardisations to determine the suitability of PPCs for each category combination. In other cases, such as the categorisation presented by Vollmann (1997b), the product dimensions are considered to be part of the market requirement category.

Beyond the extensive literature, the influence of the product dimensions on PPC selection can also be easily determined in practice. For example, a rate-based PPC approach may be more appropriate than a time-phased approach for companies with intensive production and a low variety of products could be more oriented to. Similarly, other systems, e.g., MRP, may be more appropriate for a firm in which products are comprised of multi-level components requiring assembly because this approach is more capable of managing product inventories with dependent demand (Bertrand & Muntslag, 1993) (Benton & Shin, 1998) (Ho & Chang, 2001).

The following is a brief description of the characteristics considered as part of the product dimension. These characteristics are based on descriptions provided by various authors who have incorporated them as part of a proposed framework for PPC selection.

a) Level of customisation: The level of customisation is a capability offered as part of the manufacturing strategy of many companies. Depending on the level of customisation, the selected PPCs must confront different challenges. Stevenson et al. (2005) suggested that the level of customisation directly affects the variability of product routings, with a strong influence on inventory levels or lead times. Additionally, a strong differentiation between products reduces the commonality of parts; which makes planning material requirements more complex and reduces the stability and predictability of the demand.

According to Vollmann (1997a), the product customisation in a company can be expressed using two levels: custom or standard. In contrast, MacCarthy and Fernandes (2000) proposed a broader classification, which is adopted in the framework proposed in this research. This classification includes the following four levels:

- **Customised products:** The clients design all the parameters of the product.
- **Semi-customised:** The clients design part of the product design.
- **Mushroom customisation:** Several standard products are produced according to the customer requirements. The differentiation is delayed as much as possible.
- **Standard products:** The clients do not intervene in the product design.

b) Product Mix: The product mix is a dimension related to the level of products variety produced by a company. In the frameworks proposed by Vollmann (1997a) and MacCarthy and Fernandes (2000), two levels of intensity are considered: high and low. In contrast, Silver et al. (1998) utilised a more detailed approach, with four categories that characterise the variety of products. This latter approach is utilised in the proposed framework:

- **Custom:** Few of each.
- **Many products:** Low volume.
- **Several major products:** High volume.
- **Volume commodity:** Very high production.

c) Product Structure: MacCarthy and Fernandes (2000) are among the few authors who established an explicit category for the product structure. This category describes product complexity as a function of the number of levels in the bill of materials (BOM). The product structure is herein categorised following MacCarthy and Fernandes (2000):

- **Simple products:** Products resulting from a mixture of chemical ingredients or the assembly of a few components.
- **Multi-level products:** Products requiring assembly with numerous components.

3.1.2 Processing characterization

One of the primary purposes of PPCs is supporting the production function of a company. Therefore, it is crucial that the needs of the manufacturing process correspond to the functionalities of the selected production control systems. Several operational characteristics associated with the production system should be defined to identify its correspondence with the PPCs. These characteristics should reflect the capabilities and qualities of the production system (Larsen & Alting, 1993). For example, Kochhar and McGarrie (1992) established the number of manufacturing operations, the setup times and the degree of cellular manufacturing as the key characteristics related to PPC selection. Similarly, Vollmann (1997a) suggested other characteristics, such as the production layout, the process uncertainty and the pattern of flow, as the principal characteristics of the manufacturing process that should be matched during PPC selection. The process characteristics considered relevant for PPC selection vary by author. In the proposed framework, the selection of the operational characteristics is based on a literature review of previously proposed PPC selection frameworks.

a) Process pattern: The process pattern is one the most applied categories in the PPC selection frameworks identified in the OM literature. This aspect has been described as one of the most important determining factors in the analysis of PPC applicability. Any incompatibility between the PPCs and the product flow can lead to difficulties during the planning and control phases. The process pattern dimension has been associated with the number and similarity of the machines that are part of the workstations in some studies (B. L. MacCarthy & Fernandes, 2000). However, considering the general approach of this research, the proposed framework applies the process pattern dimensions that are traditionally applied in the OM literature (Silver et al., 1998) (Stevenson* et al., 2005):

- **Job shop:** The routing sequences are random, and processing is multi-directional and multi-stage.
- **Batch flow:** The flow is jumbled, although the paths that emerge are more dominant than at a job shop.
- **Line flow:** Products flow from one operation to the next according to fixed sequencing.
- **Continuously automated rigid flow**: Products flow without stopping in the facility.

b) Setup Times: A frequent operational issue in the OM literature is the relationship between the product sequence and the time to complete setups. Thus, in case of sequence-dependent preparation times, decisions related to the releasing or the priority of the orders should consider the impact on production capacity.

Considering the general approach of this research, the proposed framework focuses on the nature of the setup times, which are classified as follows:

- **Sequence-independent setup times:** When the sequence of work in a resource does not affect its capacity.
- **Sequence-dependent setup times:** When the sequence of work in a resource affects its capacity in a significant way.

c) Production Process Information Availability: This dimension proposed by Larsen and Alting (1993) is related to the characteristics of the information maintained with respect to the production process. Depending on the PPC approach, the requirements with respect to the level of detail or volume of the information may vary by control system. Four different concepts are proposed for determining the characteristics of the information maintained with respect to the production process:

- **Accuracy:** Detailed or general information.
- **Volume:** Sparse or abundant information.
- **Time:** Out-of-date or up-to-date information.
- **Location:** Centralised or decentralised information.

d) Level of Training: Human or behavioural criteria have been highly recognised as an important dimension during the design or selection of a PPC system (Bonney, 2000) (B. MacCarthy, Wilson, & Crawford, 2001). The suitability of the level of training or the skill types developed by the shop floor operators to the requirements of a specific PPC system can vary. In this respect, this framework proposes two categories for defining the intensity of the training offered to the shop floor personnel by an individual company:

- **High operator skill:** A considerable amount of intensive training has been provided to the operators.

- **Low operator skill:** The operator training is deficient.

e) Processing time Variability: Processing time variability was suggested by Henrich et al. (2004) as a category for exploring the applicability of WLC in SMEs. Similarly, numerous papers have applied this category to determine the performance of several PPCs in environments with different levels of variability.

Process time variability was thoroughly studied by Hopp and Spearman (Hopp & Spearman, 2008), who proposed three variability classes according to the value of the CV ratio σ/t:

- **Low variability (LV):** CV < 0.75; Process times without outages.
- **Moderate variability (MV):** 0.75 <= CV<1.33; Process times with short outages.
- **High variability (HV):** CV >= 1.33; Process times with long outages.

3.1.3 Market Requirements

Market requirements are likely the most extensively studied category in the OM literature, with several studies presenting the relationship between these requirements and PPC design (Berry & Hill, 1992) (Newman & Sridharan, 1995) (Hill, 2000) (Olhager & Rudberg, 2002). According to such authors as Schroeder (1995), a mismatch between this category and a manufacturing strategy decision, such as PPC selection, can significantly affect the performance of the manufacturing firm. For example, a market requirement of maintaining high delivery reliability may lead firms to select PPCs more oriented to an MTO approach. Similarly, depending on the market strategy, firms may be more predisposed to pull instead of push PPC systems.

Based on the available literature, the importance placed on the influence of the market in PPC selection validates its inclusion in the proposed framework. The market dimensions included are selected according to their level of influence cited in previous studies. A clarification is included for the dimensions with unclear meanings.

a) Order Winner: The manufacturing strategy should accomplish the objectives that determine the competitive advantage of the company. These objectives are represented by the order winners, which are considered to be the criterion used by the companies to win orders (Choudhari, Adil, & Ananthakumar, 2012). Moreover, these objectives also represent the characteristics that allow the customers to differentiate among the products or services of different companies. Depending on the objectives of the manufacturing strategy, one PPC system may be considered more suitable than others.

Traditionally, companies have focused on no more than two of the following initiatives (Olhager & Wikner, 2000): quality, price, delivery speed, delivery reliability and flexibility.

Demand Variability: This characteristic is related to different dimensions, such as the inter-arrival time variability, variations in the volume of the demand and variability in the mix of products required by the customers. The demand variability is a primary factor in PPC selection due to its serious consequences for the company performance. High demand variability could result in excess inventory, stock-outs or elevated lead times (Bortolotti, Danese, & Romano, 2013).

Several papers in the OM literature have presented the coefficient of variation (CV) of the inter-arrival times as the primary indicator of demand variability (Bonvik, Couch, & Gershwin, 1997) (Baykoç & Erol, 1998) (Tenhiala, 2011). The CV of the inter-arrival time indicates whether order arrival times are regular or uneven. This measure characterises the variability in the flow as being of primary interest for analysing the effect of the variability on the performance of a line.

Other authors have expressed the demand variability via the CV of its volume demand (Krajewski, King, Ritzman, & Wong, 1987) (Abuhilal, Rabadi, & Sousa-Poza, 2006) (Steele, Berry, & Chapman, 1995). This indicator addresses the consistency or discrepancy of the demand for a specific product over an established period of time. Ultimately, one dimension of the demand variability is the product mix variation. This measure can be expressed using the CV of the period-to-period mix proportion (Steele et al., 1995). An alternative measure that has been applied in several papers is the standard deviation of the number of options for a specific product over a period time (Fisher & Ittner, 1999). A measure related to the variability in the mix or products is the repetitiveness. Proposed by MacCarthy and Fernandes (2000), this indicator considers a system to be less variable if a specific group of products consumes most of the available production time. The repetitiveness is based on the concept of a repetitive product, which is described as a product that consumes at least 5% of the annual available production time. According to the percentage of products that can be considered repetitive, the system can be considered more or less repetitive.

In our proposed framework, the demand variability is expressed through the following three indicators.

b) Inter-arrival time variability: According to Hopp and Spearman (2008), arrival variability can be classified as follows:

- **Low arrival variability:** $Ca \le 0.75$.
- **Moderate arrival variability:** $0.75 < Ca \le 1.33$.
- **High arrival variability:** $Ca > 1.33$.

c) Volume demand variability: Similar to the preceding indicator, the volume demand variability is measured using the coefficient of variation of the product demand for equal periods of time in a given year. The CV is calculated for a specific group of products that represent at least the 80% of the total sales. The level of variability is classified according to the following proposed categories:

- **Low volume demand variability:** At least 75% of the products present a CV <= 0.75.
- **Moderate volume demand variability:** There are a considerable number of both low- and high-variability products; alternatively, at least 75% of the products exhibit a CV between 0.75 and 1.33.
- **High volume demand variability:** At least 75% of the products present a CV > 1.33.

d) Repetitiveness level: This framework adopts the categories proposed by MacCarthy and Fernandes (2000), which range from minimum to maximum repetitiveness:

- **Purely continuous system:** Refineries.
- **Semi-continuous system:** Continuous systems with a combination of routes.
- **Mass-production systems:** Nearly all items are repetitive.
- **Repetitive production system:** At least 75% of the items are repetitive.
- **Semi-repetitive system:** Numerous repetitive and non-repetitive products.
- **Non-repetitive production system:** At least 75% of the products are not repetitive.
- **Large projects**

e) Due Date tightness: Considering the concept proposed by Henrich et al. (2004), due date tightness is associated with the slack time, which is described as the time remaining between the expected completion time of an order and its due date (Jun-Huei Lee et al., 2010). If the slack time of most committed orders is nearly zero, the environment can be categorised as having due date tightness. The proposed framework considers two categories that describe the level of due date tightness in a company:

- **High due date tightness:** Most committed orders have zero or nearly zero slack time, preventing the insertion of orders without affecting DDP.
- **Low due date tightness:** Most committed orders have slack times that allow the insertion of orders without affecting DDP.

f) Variability of due date allowances: A detailed picture of delivery reliability requires the combination of average and variability indicators (M. J. Land, 2004). In this study, the variability of due date allowances is measured using the coefficient of variation of the slack time. This coefficient results from the ratio between the standard deviation of the slack time and the average slack time. The level of variability is measured according to the variability categories proposed by Hopp and Spearman (2008):

- **Low slack time variability:** $C_{ST} <= 0.75$
- **Moderate slack time variability:** $0.75 < C_{ST} <= 1.33$
- **High slack time variability:** $C_{ST} > 1.33$

3.2 Ecuadorian SMEs characterization

The purpose of this section is to characterize the configuration of Ecuadorian manufacturing SMEs with reference to the proposed framework for PPC selection. Information regarding the configuration of Ecuadorian SMEs is based on data collected from three information sources: (a) governmental offices, such as the National Institute of Statistics and Censes (INEC), and non-governmental organisations, such as the Institute of Socio-Economical and Technological Investigations (INSOTEC); (b) a survey of 117 Ecuadorian SMEs conducted in 2008; and (c) in-depth interviews with 21 Ecuadorian manufacturing SMEs. The results with respect to the classification can be found in the following Table 3.3.

Table 3.3: Categorisation of Ecuadorian SMEs according to the proposed framework

Product Characterisation	Options	Ecuadorian SME Characterisation	
Level of customisation	• Customised products • Semi-customised • Mushroom customisation • Standard products	Mushroom customisation	In almost all MTOs, product differentiation is usually delayed as late as possible in the process.
Product Mix	• Custom • Many products • Several major products • Volume commodity	Many products	Ecuadorian SMEs offer a wide variety of products elaborated in low-volume batches.
Product Structure	• Simple products • Multi level Products	Simple products	In nearly all cases, the product structure is very simple, resulting from the mixture of chemical ingredients or the assembly of only a few components.

Process characterization	Options	Ecuadorian SMEs characterization	
Process pattern	• Job shop • Batch flow • Line flow • Rigid flow	Batch flow	Products at Ecuadorian SMEs generally flow with some randomness, although a dominant path is maintained according to the elaborated families.
Setup times	• Sequence-independent setup times • Sequence-dependent setup times	Sequence-independent setup times	In at least 80% of the cases, the sequence has no or a very weak influence on the capacity.
Production process information	❖ Accuracy: • Detailed • General ❖ Volume: • Sparse information • Abundant information ❖ Time: • Out-of-date • Up-to-date ❖ Location: • Centralised • Decentralised	• General • Sparse information • Out-of-date • Centralised	In Ecuadorian SMEs, the system for maintaining and analysing production information is precarious. This is reflected in the in-depth interviews, which revealed that 34% of the companies do not use any information system, 34% use an information system to manage production information, although this system is isolated from the rest of the systems in the company, and only 32% use an integrated information system to manage information.

Process Characterisation	Options	Ecuadorian SME Characterisation	
Level of training	• High operator skill • Low operator skill	Low operator skill	Only 27% of Ecuadorian SMEs offer regular training.
Processing time variability	• LV Processing time • MV Processing time • HV Processing time	MV Processing time	Increased preparation times and long breakdowns lead to prolonged processing times, corresponding to a moderately variable (MV) classification

Market Characterisation	Options	Ecuadorian SME Characterisation	
Order winner	• Quality • Price • Delivery speed • Delivery reliability • Flexibility to cope with changes in demand • Flexibility to offer a variety of products	Delivery reliability	Ecuadorian SMEs are essentially MTO companies with a particular interest in maintaining a highly reliable due date performance.
Inter-arrival time variability	• LV Arrivals • MV Arrivals • HV Arrivals	HV Arrivals	Companies are characterised by high variability caused by variations in the demand quantity and timing. This could be a consequence of the type of market satisfied by Ecuadorian SMEs, which are primarily integrated with large industries. SMEs do not have sufficient leverage for negotiation and are obligated to adapt to the variations based on the requirements of large corporations.
Volume Demand Variability	• LV Volume Demand • MV Volume Demand • HV Volume Demand	MV Volume Demand	Based on the data provided by the in-depth interviews, the CV of the primary products' demand was calculated. The results show that the CV generally ranges from 0.75 to 1.33.

Market Characterisation	Options	Ecuadorian SME Characterisation	
Repetitiveness level	• Purely continuous system • Semi-continuous system • Mass-production system • Repetitive production system • Semi-repetitive system • Non-repetitive production system	Repetitive production system	Although Ecuadorian SMEs can be categorised as MTO industries, the customisation is typically left to the last stage of the process in no more than two workstations. In this way, the semi-elaborated products consume a significant percentage of the annual available time.
Due date tightness	• High DD tightness • Low DD tightness	High DD tightness	Numerous competitors and a limited market have created a highly competitive environment for Ecuadorian SMEs, which has forced sales departments to go to any lengths to attract customer orders. In some cases, this implies offering due dates that challenge those offered by the competition.
Variability of Due date allowance	• Low slack time variability • Moderate slack time variability • High slack time variability	Low slack time variability	The slack time of orders is typically very limited. The long-term consistency of this pattern is confirmed by the coefficient of variation of a sample of orders. The data were collected from the 17 companies included as part of the in-depth interviews. The results reveal a CV<0.75 for nearly 70% of the cases.

3.3 PPCs Evaluation applying the proposed framework

Five PPCs approaches namely: MRP, Kanban, WLC, DBR and S-DBR were evaluated using the criteria presented in Table 3.3. A brief justification for the values assigned in each dimension is presented from Table 3.4 to Table 3.6 for the Product, Process and Market Dimensions respectively. Finally Table 3.7 facilitates a comparison and easily identifies the strengths and weaknesses of each PPC approach.

Table 3.4 Evaluation of the PPCs according to the Product Characterisation Dimensions

MRP Evaluation - Product Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Level of customisation	Mushroom customisation	-3	The application of MRP in environments characterised by high product customisation is a challenge considering the complexity of adjusting an entire system to a new product. MRP files, such as the BOM, should be created as soon as an order is placed (Chen, Miao, Lin, & Chen, 2008).
Product mix	Many products	+9	The MRP system was originally designed as a software package for maintaining files associated with bills of materials and routings, which are related to the inventory masters (Ptak & Smith, 2011). Therefore, this system was initially conceived to manage high volumes of information for a large variety of products (T. E. Vollmann et al., 1997a) (Nahmias & Cheng, 2009).
Product structure	Simple products	+1	One characteristic of MRP is the introduction of the BOM as a tool to characterise the relationships between the end- and lower-level items (Hopp & Spearman, 2008), allowing easy management of products consisting of many parts and subassemblies (Bertrand & Muntslag, 1993). Therefore, the presence of simple products in the Ecuadorian context does not affect the effectiveness of the MRP application, although it does not take advantage of this capacity.

Kanban Evaluation - Product Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Level of customisation	Mushroom customisation	-3	The Kanban system has traditionally been considered appropriate for a repetitive environment with few products and limited engineering changes (Abuhilal et al., 2006). In fact, in the literature, the major successful Kanban implementations have been reported in environments in which the demand can be accurately predicted and product variety can be constrained (Akturk, Erhun, 1999).
Product mix	Many products	-9	Kanban requires a buffer of material for each stage of the process (Baynat, Dallery, Mascolo, & Frein, 2001) and for each of the elaborated products. This requirement makes Kanban poorly suited for multi-product environments in which a wide variety of products can be elaborated and a uniform workload may be difficult to attain (FINCH & Cox, 1986) (Stevenson* et al., 2005).
Product structure	Simple products	+9	A reduced number of components implies a reduction in the stock required to allow a customer’s order to be pulled along the value stream (Spearman, Woodruff, & Hopp, 1990) (Hopp & Spearman, 2008). This characteristic makes Kanban less susceptible to an increase in inventory levels for component parts (Krajewski et al., 1987).

Workload Control Evaluation - Product Characterisation			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Level of customisation	Mushroom customisation	+9	The WLC system is designed specifically for MTO environments, whereby different products are designed for different customers (Henrich et al., 2004). In fact, WLC has been presented as suitable for the large variety of products (Hoeck, 2008) required to meet increasing customer expectations in modern markets (Mark Stevenson & Hendry, 2006).
Product mix	Many products	+9	Several papers have presented WLC as a suitable choice for complex environments characterised by substantial product variety. The semiconductor industry (Eivazy, Rabbani, & Ebadian, 2009) and an MTO electric motor company (Park, Song, Kim, & Kim, 1999) are among the examples demonstrating that WLC is particularly relevant for companies with a large variety of products.
Product structure	Simple products	+9	For WLC systems, jobs are released to the pre-shop floor after they have been accepted by the entry stage and the materials become available (Mark Stevenson, 2006). Therefore, fewer components may lead to reduced task complexity. In fact, some authors, such as Stevenson and Silva (2008), presented empirical evidence of WLC applications in which the product complexity affects the calculation of due dates.

Drum-Buffer-Rope - Product Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Level of customisation	Mushroom customisation	+9	Several papers have described the effective application of DBR in highly customised environments, such as make-to-order (MTO) (Guo & Qian, 2006) (Jun-Huei Lee et al., 2010) or engineering-to-order (ETO) (Wahlers & Cox III, 1994) manufacturing scenarios. Focusing on only one internal resource makes DBR easy to implement in highly customised environments where it may be difficult to estimate the required processing times for all resources (Stevenson* et al., 2005).
Product mix	Many products	+3	DBR has been presented as a suitable choice for companies with a high product mix. For example, Klusewitz and Rerick (1996) presented a DBR implementation at a wafer facility, which required the effective management of the product mix. However, the implicit assumption of a stationary bottleneck (Stevenson* et al., 2005) may be a limitation for environments where the product mix significantly influences a shift in the bottleneck (Steele*, Philipoom, Malhotra, & Fry, 2005).
Product structure	Simple products	+9	Traditionally, DBR requires three buffers: the constraint, the shipping and the assembly buffers (E. M. Goldratt, 1990). The lack of assembly operations in most Ecuadorian products avoids the requirement of an assembly buffer, which simplifies the priority list of orders and increases the flexibility to meet the requirements of the clients.

Simplified Drum-Buffer-Rope - Product Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Level of customisation	Mushroom customisation	+9	S-DBR is presented as a flexible system in which the inclusion of new products does not cause chaos. The lack of added chaos is due to the planning simplicity, which is based on only one buffer, and the lack of a planning sequence for the CCR (Schragenheim & Dettmer, 2000b) (Schragenheim, Weisenstern, & Schragenheim, 2006a).
Product mix	Many products	+9	The presence of multiple products is not a barrier for a system in which protection based on WIP is replaced by buffer times. This approach provides the necessary protection without maintaining an expensive safety stock for each product (Schragenheim & Dettmer, 2000a). Additionally, in practice, one buffer time is set for one or more families, and process time estimates are not needed for each product (Hwang, Huang, & Li, 2011).
Product structure	Simple products	+9	According to S-DBR, all materials required for an order are released at the same time (Schragenheim & Dettmer, 2000b). This characteristic makes S-DBR a simple production planning methodology. However, for a product requiring many components, maintaining just one shipping buffer is not sufficient to control variations at assembly points. In Ecuadorian SMEs, products are very simple; consequently, S-DBR may be suitable for Ecuadorian SMEs.

Table 3.5 Evaluation of the PPCs according to the Process Characterisation Dimensions

MRP - Process Characterization			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Process pattern	Batch flow	-3	Traditionally, MRP has not been capable of providing planning and control in the case of variable shop floor routings (Stevenson* et al., 2005) due to its assumption of maintaining standard products and routings (Muntslag, 1993).
Setup times	Sequence-independent setup times	+9	Numerous works have studied the nervousness of MRP systems (Stevenson* et al., 2005). This property is related to the strong effects on the timing and quantity dimensions of the lower components that result from small changes in the demand for a final products (Cox, Blackstone, & Spencer, 1995) (Hopp & Spearman, 2008). At Ecuadorian SMEs, independent setups reduce adjustments in MPS sequences, which has a positive effect for the implementation of MRP.
Production process Information	General Sparse Out-of-date Centralised	-9	MRP has a critical requirement regarding the volume and accuracy of information (S. L. Koh, Saad, & Padmore, 2004). This aspect is an important challenge for the personnel and technological systems related to information collection and management (Wilson, Desmond, & Roberts, 1994).

MRP - Process Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Level of training	Low operator skill	-9	MRP is a complex system, and the probability of a successful implementation varies according to the level of preparation and experience of the firm's personnel (Petroni & Rizzi, 2001) (Petroni, 2002). For example, to maintain stock accuracy, operators must always input the correct information at the correct time (Wilson et al., 1994). Among Ecuadorian SMEs, the operators at most companies are poorly trained and largely uneducated.
Processing time variability	Moderate processing time variability	-3	MRP assumes fixed planned lead times; thus, any variation in the process, such as prolonged machine breakdowns or excessive setup times, may significantly alter the planned order release (POR) schedule (S. L. Koh et al., 2004). In accordance with these criteria, MRP is primarily designed for operation in stable and predictable manufacturing environments (Wijngaard & Wortmann, 1985).

Kanban - Process Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Process pattern	Batch flow	-3	Traditionally, in the OM literature, Kanban has been studied in pure flow shop environments (Rodríguez, Franco, & Vázquez, 1998) (Stevenson* et al., 2005). This environment represents an ideal situation in which orders flow from one workstation to another in a deterministic manner (Davis & STUBITZ, 1987). The lack of a strict order in the sequence of the work centres can generate difficulties for demand forecasting and shop scheduling (Gargeya & Thompson, 1994).
Setup times	Sequence-independent setup times	+9	Although most of the literature is related to reducing setup times, the presence of sequence-dependent setup times is an important issue in the Kanban literature. The planning problem appears when the setup times are influenced by the sequence of decisions (Missbauer, 1997). Sequence-independent setup times avoid the inclusion of a setup change protocol for deciding which setup should be developed next and when (Krieg & Kuhn, 2004).
Production process information	General Sparse Out-of-date Centralised	+9	The Kanban system can be categorised as a non-computerised system, which is described as a production scheduling control method focused on shop floor physical operations (Ho & Chang, 2001) that utilises cards to control the flow of materials throughout the production process (Modarress, Ansari, & Willis, 2000). Therefore, Kanban does not require status information of the same accuracy as MRP (C. Y. Lee, 1993), making this system much more suitable for companies that struggle to exploit IT technology.

Kanban - Process Characterisation			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Level of training	Low operator skill	+9	Several studies have reported the effectiveness of training activities during the Kanban implementation process, even in cases in which employees have a low level of education (Silva & Sacomano, 1995). The simplicity of Kanban over push systems (Chaudhury & Whinston, 1990) (T.-M. Chang & Yih, 1994) contributes to the favourability for system implementation in Ecuadorian SMEs.
Processing time variability	Moderate processing time variability	-3	Several authors have examined the influence of variability on the performance of Kanban systems. For example, Mascolo et al. (1996) analysed the influence of processing time variability on the proportion of backordered demands. Their results showed that when CV^2 exceeds 1, the backordered demand tends to increase significantly. Similar results were presented in the work of Koukoumialos and Liberopoulos (2006), where processing times with cv^2 exceeding 1 were found to significantly reduce the production capacity of a system. The moderate variability indicative of processing times in Ecuadorian SMEs may affect the performance of the Kanban implementation.

Workload Control - Process Characterisation			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Process pattern	Batch flow	+9	WLC addresses the dynamic circumstances of job shops (M. Land & Gaalman, 1996). Considering its flexibility, WLC is suited to address complex situations that are typically present in real cases (L Hendry, Land, Stevenson, & Gaalman, 2008) (Eivazy et al., 2009).
Setup times	Sequence-independent setup times	+9	One of the essential elements of WLC is the control point at the release stage. According to Henrich et al. (2004), once orders have been released, they should follow a simple priority rule to control their progress. This rule may be infeasible for sequencing-dependent setups, which may require joint progress control of the orders released on the shop floor.
Production process information	General Sparse Out-of-date Centralised	-9	The information and IT requirements for implementing WLC are modest relative to those of other planning and control initiatives (Fowler, Hogg, & Mason, 2002). However, WLC requires accurate and up-to-date information on an order's progress (Wiendahl, 1995). This aspect is one of the main barriers prohibiting the successful implementation of WLC in an environment similar to that of Ecuadorian SMEs, which is characterised by sparse, out-of-date, general and centralised shop floor information.

Workload Control - Process Characterisation			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Level of training	Low operator skill	-9	Similarly to MRP, the WLC methodology requires copious amounts of accurate data to provide feedback regarding job progress (Mark Stevenson & Hendry, 2006). For example, WLC proposes a sequencing procedure that requires continuous information about the buffer contents issued on the CCRs (Riezebos, Korte, & Land, 2003). Most of this information is directly determined from the shop floor and provided by shop floor personnel. Therefore, in an environment similar to Ecuadorian SMEs, unskilled operators and deficient training programs may be important barriers for a successful WLC implementation.
Processing time variability	Moderate processing time variability	+9	WLC is a PPC designed for real conditions, which is partly achieved by considering processing times as random variables (M. J. Land, 2004). Some authors have suggested that WLC is perfectly suited for processing times with a high level of variability (Henrich et al., 2004). Considering the moderate level of variability in the processing times of Ecuadorian SMEs, it is possible to categorise WLC as a suitable system for this environment.

Drum-Buffer-Rope - Process Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Process pattern	Batch flow	+3	Several studies have reported that DBR performs well as a control mechanism for job shop environments, even in the case in which different routings have different bottleneck operations (Chakravorty, 2001) (M. Gupta, Ko, & Min, 2002). However, DBR performance may be limited by the flexibility of a system, especially considering that any change at the CCR location requires adjusting the schedule (Schragenheim, Weisenstern, & Schragenheim, 2006b). Most Ecuadorian SMEs utilise a batch flow configuration. Therefore, it is likely that bottlenecks will remain relatively stationary and deterministic (Stevenson* et al., 2005).
Setup times	Sequence-independent setup times	+9	DBR offers a planning system that is closely related to the inherent complications of sequence-dependent setups (Schragenheim & Dettmer, 2000b) (Schragenheim et al., 2009c). As a general approach, Ecuadorian SMEs typically exhibit sequence-independent setup times. This characteristic may offer DBR additional flexibility to respond to market demands.
Production process information	General Sparse Out-of-date Centralised	+9	Focusing primarily on CCRs substantially reduces the volume of required information. Previous implementation experiences have demonstrated that the amount and the level of detail required for the information in a DBR implementation is small for repetitive production systems, e.g., like that typically used in Ecuadorian SMEs (Panizzolo & Garengo, 2013)

Drum-Buffer-Rope - Process Characterisation			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Level of training	Low operator skill	+1	DBR implementation requires that all operators on the shop floor be trained and reorganised to take immediate actions necessary to overcome systemic conflicts (Wahlers & Cox III, 1994) (Cox III & Spencer, 1998). This requirement may be a barrier for some environments, such as Ecuadorian SMEs, where there is a lack of formal training programs. However, several papers have noted the relative simplicity of DBR with respect to other PPC systems (Fry, Karwan, & Steele, 1991) (Schragenheim & Dettmer, 2000c) (Ajoku, 2007).
Processing time variability	Moderate processing time variability	-3	Several studies have evaluated the performance of DBR in terms of stochastic processing times, suggesting a significant increase in waiting times and WIPs when moving from low-variability to high-variability cases (Betterton & Cox III, 2009). In the case of DBR, disruptions and variance in the manufacturing process are buffered via buffer times (S.-Y. Wu, Morris, & Gordon, 1994). As for any other protection, the extent of the benefits depends on the amount of variability in the system (Kadipasaoglu, Xiang, Hurley, & Khumawala, 2000). Consequently, a moderate variability will require moderate lead times, which may reduce the due date tightness typically present in this environment.

Simplified Drum-Buffer-Rope - Process Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Process pattern	Batch flow	+3	Schragenheim (2009c) proposed that a shop floor with frequent CCR location changes may be a complicated environment for the implementation of a S-DBR system because random routing sequences increase the likelihood that a bottleneck will not remain stationary over long periods of time. Consequently, S-DBR is a system that is much better suited to regular environments, such as batch flow (Stevenson* et al., 2005), which is the process pattern configuration that is more frequently used by Ecuadorian SMEs.
Setup times	Sequence-independent setup times	+9	S-DBR is characterised by its simplicity, which is a consequence of maintaining a less detailed planning algorithm and managing only one buffer time (Schragenheim & Dettmer, 2000a). However, these characteristics may represent a limitation for handling very complex production processes (Schragenheim et al., 2009c). One such case is the presence of dependent setups requiring a sequence that is not necessarily determined by the market to protect the capacity of the CCR (Schragenheim et al., 2006b).
Production process information	General Sparse Out-of-date Centralised	+9	According to the S-DBR concepts, the market is considered the principal constraint and is protected with only one buffer (Schragenheim et al., 2006b). This practice considerably reduces the volume of information required, facilitating its implementation in environments with low IT levels. In fact, empirical evidence indicates that S-DBR allows control to be sustained based on visual management, i.e., without information systems to maintain the control of operations on the shop floor (Hwang et al., 2011).

Simplified Drum-Buffer-Rope - Process Characterisation			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Level of training	Low operator skill	+9	Numerous experiences have presented S-DBR as a PPC system that is highly suited for environments characterised by low-skilled labour. For example, Sedano (2011) and Alvarez (2013) presented successful results in 84 Colombian SMEs and 15 Ecuadorian SMEs. Most of these companies can be characterised by the presence of shop floor operators with a low level of training and education.
Processing time variability	Moderate processing time variability	+3	S-DBR relies heavily on the quality of the decisions made during execution, resulting in less detailed planning (Schragenheim et al., 2006b). Based on this principle, S-DBR does not require a standard process time for each elaborated product. The buffer time can be set as the lead time for each product family (E. Goldratt, 2006). Consequently, any small or moderate variation in the processing times of Ecuadorian SMEs can be considered part of the established buffer.

Table 3.6 Evaluation of the PPCs according to the Market Requirements

MRP – Market Requirements			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Order winner	Delivery reliability	-9	MRP has important limitations for satisfying the high reliability requirement of MTO sectors. The MRP system lacks a customer enquiry stage for due date determinations based on capacity planning (Stevenson* et al., 2005). Additionally, MRP does not include mechanisms to control the entry and release time of orders based on DDP. Other authors have stated that the inability of MRP to achieve a highly reliable DDP is a result of its separation of the analysis of material flow from that of capacity (Benton & Shin, 1998; M. Gupta & Snyder, 2009).
Inter-arrival time variability	High inter-arrival time variability	-3	Inter-arrival time variability is a problem for rigid MRP systems characterised by difficulties in adapting the uncertain nature of production operations to planning (Benton & Shin, 1998). In fact, several authors have considered MRP to be a flawed model based on its rigid assumptions and excessive sensitivity to such changes (Mbaya, 2000).
Volume demand variability	Moderate volume demand variability	-3	The constant presence of demand volume fluctuations make MRP nearly incapable of developing detailed sales forecasts (Bertrand & Muntslag, 1993). One consequence of MRP implementation is a cost increase due to the excess inventory required to protect against the variations in the demand volume (Yeung, Wong, & Ma, 1998). Additionally, the presence of forecast variations can significantly impact system performance and reduce the service level of the company (Zhao & Lee, 1993).

MRP – Market Requirements			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Repetitiveness level	Repetitive production system	+9	As for any other measure of demand variability, the presence of a variable product mix can induce a deviation from the original plans (Ptak & Smith, 2011). A non-repetitive production system can constantly change its depiction of the MPS that is driven by an increase in protection inventory. The presence of a repetitive production system avoids these consequences and may be beneficial for MRP implementation.
Due date tightness	High DD tightness	-9	According to Stevenson et al. (2005), in an environment characterised by due date tightness, the selected PPC must consider such criteria as the inclusion of job entry and job release stages aimed to promote due date adherence. MRP lacks this type of element (Henrich et al., 2004). Order release times are based on a flawed model in which both lead times are fixed and there is infinite capacity (Mbaya, 2000).
Variability of due date allowance	Low slack time variability	+3	Both safety stock and lead times should be adjusted to achieve the desired DDP in MRP systems (Benton, 1991) (Enns, 2001) (Enns, 2002). The results indicate that increasing the lead times and adding safety stock positively influences the DPP. In both cases, these solutions increase the work in process levels and decrease MRP performance. In the case of Ecuadorian SMEs, a low due date allowance variability may be considered an incentive for its implementation by not requiring frequent adjustments in these protective measures.

Kanban– Market Requirements			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Order winner	Delivery reliability	-9	Kanban lacks the elements required for MTO manufacturing companies to achieve good due date performance. Various elements, including customer enquiry, job entry and job release stages, are not considered to be part of the standard Kanban framework (Stevenson* et al., 2005). Several application case studies have presented evidence of the poor due date performance of Kanban. For example, Huq (1999) provided evidence that Kanban leads to reduced due date performance (tardiness) compared with conventional shop control techniques.
Inter-arrival time variability	High inter-arrival time variability	-3	Similar to processing time variability, the performance of Kanban can decrease significantly as the inter-arrival time variation increases (Boonlertvanich, 2005). For example, Bonvik and Gershwin (1997) showed that Kanban has a higher total inventory than CONWIP and hybrid systems in the case of changing demand rates.
Volume demand variability	Moderate volume demand variability	-3	Kanban is a system that is suitable for environments with standard products elaborated at a high volume and with low variability in demand levels (Akturk & Erhun, 1999). Large variations in demand could destroy the flow and undermine the performance of this type of system (Deleersnyder, Hodgson, Muller-Malek, & O'Grady, 1989) (CHATURVEDI & GOLHAR, 1992) (Marek, Elkins, & Smith, 2001). Under such environments, changes in product volume lead to high costs as a result of production re-scheduling and capacity changes (T. Vollmann, 2005).

Kanban– Market Requirements			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Repetitiveness level	Repetitive production system	+9	Environments with a high level of repetitiveness have traditionally been considered suitable for Kanban implementations (Abuhilal et al., 2006), as reflected in the level of success reported in repetitive manufacturing environments (Akturk & Erhun, 1999).
Due Date Tightness	High DD tightness	-9	Kanban is characterised by a reduction in the level of WIP (Chung, Yang, & Cheng, 1997). Consequently, it may be expected that its implementation would result in a reduction in manufacturing lead times and an improvement in due date performance. However, several previous case studies, such as those presented by Jodlbauer and Huber (2008) and Huq (1999), have reported that the Kanban system can achieve a lower service level than other PPC systems. These results are consistent with previous studies that have presented Kanban as a system not suitable for an MTO environment (Stevenson* et al., 2005), where a highly reliable due date performance is crucial.
Variability of due date allowance	Low slack time variability	+3	In a Kanban system, given certain parameters, it is possible to achieve the expected service level performance. However, under dynamic conditions, it may be difficult to maintain the required long-term PPC performance.(S. M. Gupta & Al-Turki, 1997). For example, Jodlbauer and Huber (2008) compared Kanban and other PPC systems in terms of service level and found that Kanban requires extra parameters to maintain the service level under different variability conditions. Additionally, the increase in the number of parameters relative to other PPCs, such as CONWIP or DBR, make Kanban a system with limited flexibility (Jodlbauer & Huber, 2008). Therefore, a low due date allowance variability can be considered as an incentive for its implementation by obviating the frequent adjustment of its parameters.

Workload Control– Market Requirements			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Order winner	Delivery reliability	+9	Monitoring lead times by controlling workloads is a fundamental principle of WLC (Wiendahl, 1995) and is relevant to the MTO company characteristics that facilitate a highly reliable due date (Henrich et al., 2004). This notion is supported by numerous papers claiming that WLC focuses on MTO requirements, including a high DDP. Stevenson et al. (2005) noted that WLC was originally designed to attain a high DDP by incorporating a customer enquiry stage that considers the total backlog of a shop in the DD determination and job entry and job release stages that focus on DD adherence.
Inter-arrival time variability	High inter-arrival time variability	+9	Several authors have analysed the effect of inter-arrival time variability on the performance of WLC (Henrich et al., 2004) (Henrich, 2005) (M Stevenson & Silva, 2008). In most cases, WLC has been found to have the necessary means, such as a pool of jobs, to absorb fluctuations in arriving orders (M. J. Land, 2004). These mechanisms result in a more regular arrival pattern of work to workstations and make WLC suitable for environments with high or moderate inter-arrival time variability (Henrich et al., 2004).
Volume demand variability	Moderate volume demand variability	-3	According to Henrich (2004), the WLC approach is designed to function when workloads are composed of numerous jobs with short processing times. This characteristic supports the assumption that the variation within the sum of the processing times is relatively small and that the workload norms can generate a predictable lead time.

Workload Control– Market Requirements			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Repetitiveness level	Repetitive production system	+9	WLC is a system designed to support the required flexibility of low-volume job shop production (LC Hendry, Kingsman, & Cheung, 1998) (Zozom Jr, Hodgson, King, Weintraub, & Cormier, 2003) (Hoeck, 2008). Consequently, a repetitive environment facilitates its implementation.
Due date tightness	High DD tightness	-9	Tight due dates are in conflict with the level of resource buffering exhibited by WLC. Therefore, in this case, it is critical to rely on high-capacity flexibility resources that avoid queues and achieve the required service level (Henrich et al., 2004).
Variability of due date allowance	Low slack time variability	+9	According to the WLC concepts, the variability of due date allowances can be compensated by the time that jobs remain in the order pool (Henrich et al., 2004). For Ecuadorian SMEs, the presence of a low due date allowance require a limited waiting pool time, which does not significantly affect the due date achievement, one of the primary requirements of Ecuadorian SMEs.

Drum-Buffer-Rope– Market Requirements			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Order winner	Delivery reliability	+9	DBR offers a customer enquiry stage that provides realistic due dates based on the finite capacity of the CCR (Cox III & Spencer, 1998). Additionally, to provide DDs, this stage determines the acceptance of an order, which serves as the first opportunity to influence flow on the shop floor. Finally, DBR uses a mechanism that releases orders based on the processing capability of the CCR (Chakravorty, 2001) and monitors their advancement using buffer management methodology, which provides more reliable delivery to the customers (Mabin & Balderstone, 2003).
Inter-arrival time variability	High inter-arrival time variability	+9	DBR is frequently utilised in MTO production scenarios despite the claims of some authors that it does not place the necessary importance on planning and controlling at the job entry stage (Stevenson* et al., 2005). However, the mechanism proposed by DBR for entering jobs based on the CCR workload has performed well, even in complex cases, such as the job shop environment (Chakravorty, 2001). The proposed system is used to control the total amount of work, which decreases the impact of inter-arrival time variability.
Volume demand variability	Moderate volume demand variability	-3	Volume demand variability can result in a wandering bottleneck, which requires constant schedule updates and results in a change in the resource constraint station (Cox III & Spencer, 1998) (Mark Stevenson & Hendry, 2006). This effect can seriously affect the principal assumption of any DBR implementation related to maintaining a stationary bottleneck (Stevenson* et al., 2005). Consequently, in the case of a high demand variability, it is necessary to monitor machine loads to prevent this phenomenon (Hadas, Cyplik, & Fertsch, 2009).

Drum-Buffer-Rope– Market Requirements			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Repetitiveness level	Repetitive production system	+9	As a measure related to the product mix, the level of repetitiveness can influence the probability of shifts in bottlenecks (Cox III & Spencer, 1998). A low level of repetitiveness may result in frequent changes in the physical constraint, implying the occurrence of the wandering bottleneck effect (Tseng & Wu, 2006). Although some authors have concluded that the probability of changes in production order combinations that cause a bottleneck shift is fairly low (Hurley & Kadipasaoglu, 1998), a highly variable environment can be considered to be more prone to such a scenario. Ecuadorian SMEs exhibit a high repetitiveness level, strongly reducing the likelihood of this type of effect.
Due date tightness	High DD tightness	-3	DBR provides highly reliable DDs by releasing orders before they are scheduled according to a buffer of time (Schragenheim & Dettmer, 2000a). These buffers are a form of safety lead times and represent a possible protection against schedule disruptions (Guide Jr, 1996). The buffer length depends on the presence of breakdowns, fluctuations in the setup times, absenteeism and even the unavailability of a certain resource (Schragenheim & Ronen, 1989). Therefore, certain environments, such as Ecuadorian SMEs, should place great importance on reducing these sources of variability to continue offering competitive due dates without sacrificing delivery reliability.
Variability of due date allowance	Low slack time variability	+9	According to the DBR methodology, established lead times should recognise the market demand requirements (Schragenheim, 2006). Consequently, environments with a high variability in due date requirements may result in confusion over priorities. Fortunately, the market of Ecuadorian SMEs exhibits a relative stationary requirement regarding the length of due dates, further facilitating the implementation of this methodology.

Simplified Drum Buffer Rope– Market Requirements			
Dimension	**Ecuadorian Characterization**	**Score**	**Justification**
Order Winner	Delivery Reliability	+9	S-DBR is highly recommended for companies that require very reliable due date performance (DDP). For example, Lee et al. (2009) cited S-DBR as a mode of managing operations for improving DDP. In fact, most of the literature suggest S-DBR as an improvement program for DDP with successful results (Jiun-Huei Lee et al., 2009) (Jun-Huei Lee et al., 2010) (Hwang et al., 2011).
Inter arrival time variability	HV Arrivals	+3	S-DBR utilises a job release stage that is directly related to the CCR capacity planning. Because materials are only released half of the buffer time prior, the order is supposed to be determined by the CCR (Schragenheim, 2006). Consequently, orders remain in a pre-shop pool of orders, increasing the manageability of highly variable inter-arrival times. This mechanism significantly reduces congestion on the shop floor and facilitates control by only working with orders that are planned to be delivered within a pre-defined horizon (E. Goldratt, 2006).
Volume Demand Variability	Moderate variable Volume Demand	-3	The principal risk of high volume demand variability is the emergence of temporary bottlenecks at resources that are not typically CCRs (Schragenheim et al., 2009c) generated by oversized orders. Under this circumstance, S-DBR suggest that the clients should divide an order into smaller deliveries, reducing the pressure on the manufacturing operations (E. Goldratt, 2006) while maintaining the advantages of a large order.

Simplified Drum-Buffer-Rope– Market Requirements			
Dimension	**Ecuadorian Characterisation**	**Score**	**Justification**
Repetitiveness level	Repetitive production system	+9	For a company in which a repetitive group of products consumes a significant percentage of production time, it is likely that bottlenecks remain relatively stationary (Cox III & Spencer, 1998), which can have the same effect as maintaining a general flow shop or a pure flow shop, where bottlenecks can even be considered deterministic (Stevenson* et al., 2005).
Due Date tightness	High DD tightness	-9	Schragenheim, the creator of the S-DBR methodology, suggested the reservation of capacity as an option to complete orders faster than regular orders (Schragenheim, 2006). This approach may be an effective option, although it is also costly (Jun-Huei Lee et al., 2010) and consequently not attractive for Ecuadorian SMEs. For such cases, Lee et al. (2010) proposed an enhancement to the S-DBR methodology that is based on the available slot time in the CCR. The proposed method considers the slack time to determine whether an urgent order can be accepted or a committed order can be brought forward. Considering the high due date tightness characteristic of Ecuadorian SMEs, neither of the proposed methodology for the insertion of orders is suitable.
Variability of due date allowance	Low slack time variability	+9	An environment such as the Ecuadorian SMEs, where due dates are stable, may benefit from an approach like S-DBR, which can handle significant static lead times (E. Goldratt, 2006).

3.4 Proposed PPCs based on Ecuadorian SME characteristics

Having completed the suitability analysis, it was possible to identify the weaknesses and strengths of each system based on Ecuadorian SME characteristics. A summary of the previous data is presented in Table 3.7, where S-DBR has the highest score among the evaluated PPCs. The lowest scores correspond to the systems that are not traditionally considered suitable for an MTO environment, such as MRP and Kanban.

MRP has not been positively associated with MTO operational issues, which is at least partially due to its inability to provide proper planning in the presence of variable shop floor routings (Stevenson* et al., 2005) and the rigid assumptions related to fixed lead times (Muntslag, 1993) (Mbaya, 2000). The consequence is a system with excessive sensitivity to changes, which is not suitable for the agile and highly turbulent environment of Ecuadorian SMEs. Additionally, MRP has other important limitations for satisfying the requirement of the MTO sector in Ecuadorian SMEs, such as the lack of a customer enquiry stage for determining due dates (Stevenson* et al., 2005) (M. Gupta & Snyder, 2009) and the ability to control the entry and release of orders by focusing on DDP (Henrich et al., 2004).

With respect to demand, strong volume demand fluctuations can limit MRP implementations due to the difficulty of developing a detailed sales forecast, which is one of the primary inputs for MRP (Bertrand & Muntslag, 1993). Consequently, the moderate variability exhibited by Ecuadorian SMEs may be a risk for MRP implementation. The consequences could be a cost increase resulting from the excess inventory required to protect against demand uncertainty (Yeung et al., 1998).

Another possible limitation is related to the high volume and accuracy of information required for managing this type of system (Petroni & Rizzi, 2001) (S. L. Koh et al., 2004). The previous literature has suggested that the variation in the probability of a successful MRP implementation varies according to the level of preparation and experience of the personnel in charge of the collection and processing of the required data (Wilson et al., 1994) (Petroni, 2002). Consequently, an MRP implementation may require a considerable amount of training and investment in IT systems for Ecuadorian SMEs.

Finally, MRP is associated with software packages designed to manage high volumes of information, typically related to many products composed of numerous parts and subassemblies (Bertrand & Muntslag, 1993). This is a non-critical characteristic in an environment where products are composed of few components, such as in Ecuadorian SMEs. Additionally, the application of MRP in an environment characterised by frequent customisation requires the constant generation of MRP files (Chen et al., 2008), which may present a challenge considering the lack of agility in the business processes of Ecuadorian SMEs. The unique positive point that supports MRP implementation in Ecuadorian SMEs is the repetitiveness that distinguishes this market. Despite the variety of products, most of the capacity is employed for only a few articles. One of the few points that positively influences MRP implementation is the sequence-independent setup times exhibited by Ecuadorian SMEs, which correspond to the MRP principle that assumes fixed planned lead times (S. L. Koh et al., 2004). Similarly, a low due date allowance variability is an incentive for the implementation of MRP due to the frequent adjustment of its protective measures, such as safety stocks or lead times factors, which significantly affect the DDP of MRP (Benton, 1991) (Enns, 2001) (Enns, 2002).

Meanwhile, the Kanban system has been traditionally associated with repetitive environments with few products and limited engineering changes (FINCH & Cox, 1986) (Akturk, Erhun, 1999) (Abuhilal et al., 2006). One reason for this association is the requirement of maintaining inventory buffers at each stage of the processes and for each product (Baynat et al., 2001). In this way, the product differentiation and the wide variety exhibited by Ecuadorian SMEs limits its application. In the product category, the only positive point for Kanban is product simplicity, which allows a reduction in the component stock required for a customer order to be pulled along the value stream (Spearman et al., 1990) (Hopp & Spearman, 2008).

Traditionally, in the OM literature, Kanban has been applied in pure flow shop environments (Rodríguez et al., 1998) (Stevenson* et al., 2005). These environments are an idealisation of reality, where orders flow from one workstation to another in a deterministic manner (Davis & STUBITZ, 1987). However, this flow differs from the actual flow pattern of Ecuadorian SMEs, which are closer to a general flow shop. In this case, the lack of a strict order in the sequence of the work centres can generate complications in the Kanban implementation, resulting in difficulties in demand forecasting and shop scheduling (Gargeya & Thompson, 1994).

Additionally, the variability exhibited by Ecuadorian SMEs can negatively influence the performance of Kanban systems. Mascolo et al. (1996) and Koukoumialos and Liberopoulos (2006) showed that processing times in which cv2 exceeds 1 significantly reduce the production capacity of a Kanban system. Similarly, the inter-arrival times (Bonvik et al., 1997) (Boonlertvanich, 2005) and the volume demand variability exhibited by Ecuadorian SMEs can destroy the flow and undermine the performance of this type of system (Deleersnyder et al., 1989) (CHATURVEDI & GOLHAR, 1992) (Marek et al., 2001).

Similar to other traditional PPC systems, Kanban is not considered suitable for MTO environments. One of the reasons is the lack of elements utilised to achieve a high DDP, such as a customer enquiry stage and job entry and job release stages (Stevenson* et al., 2005). In fact, several application case studies have presented evidence of the poor due date performance of Kanban relative to conventional shop control techniques (Huq, 1999). Despite the low due date allowance variability that is indicative of Ecuadorian SMEs, this performance may be considered as an incentive for Kanban implementation because frequent parameter adjustments are not required.

Despite its numerous drawbacks, Kanban may provide some benefits in Ecuadorian SMEs. For example, the sequence-independent setup times significantly facilitate Kanban by avoiding the inclusion of setup change protocols (Krieg & Kuhn, 2004). Similarly, the repetitiveness presented in this evaluation context is considered suitable for Kanban implementations (Akturk & Erhun, 1999) (Abuhilal et al., 2006). Additionally, Kanban is a non-computerised system that is focused on shop floor physical operations (Ho & Chang, 2001) and primarily utilises visual systems instead of sophisticated software to control the flow of materials (Modarress et al., 2000). Consequently, Kanban does not require highly accurate and large volumes of information (C. Y. Lee, 1993) (Chaudhury & Whinston, 1990) (T.-M. Chang & Yih, 1994), which significantly reduces the training requirements and minimises the need for highly skilled operators.

Among the systems that are better suited to the MTO environment, WLC has the lowest score. This low score is primarily due to the substantial amount of information necessary to maintain this system, where feedback with respect to the order status is critical. As a result, the

WLC system has a high IT requirement, needing highly trained personnel who diligently maintain the accuracy of a massive volume of production information.

Another reason for its lack of suitability is related to the violation of one of its primary assumptions. The demand is not necessarily comprised of many orders with small processing times in the Ecuadorian SME market. Finally, the high due date tightness of the Ecuadorian market may conflict with a system based on maintaining queues in front of each resource. Similarly, the incorporation of a pool waiting time as part of the WLC system is not necessarily compatible with the limited due date allowance of the Ecuadorian SME market.

In comparison to WLC, DBR is a more suitable option, with a significantly superior score. The reduced requirements concerning information volume and accuracy make DBR more suitable for companies with a low IT level.

Additionally, the mechanism proposed by DBR for monitoring orders is significantly simpler and requires much less information than that proposed by WLC. This mechanism, called buffer management (BM), can be implemented as a visual control and, in conjunction with a continuous improvement system, is primarily aimed at improving DDP. This characteristic is in agreement with high delivery reliability and the order winner for most Ecuadorian SMEs. Additionally, in contrast to WLC, volume demand variability has a limited impact on planning. The presence of ultra-large orders alone can generate a posterior problem by creating temporary bottlenecks.

Although DBR appears to be a better option than WLC, it still has limitations that prevent it from being perfectly suitable for Ecuadorian SMEs. These limitations are related to a lack of flexibility resulting from its primary focus on maximising the exploitation of its internal

CCR, which typically results in especially complex CCR scheduling that struggles to adapt to changes. A small market fluctuation can cause a significant change in scheduling and significantly affect the promised due dates.

The simplicity of S-DBR, which is based on maintaining only one buffer and the lack of detailed CCR scheduling, makes this system a flexible option for environments with a frequent inclusion of new products (Schragenheim et al., 2006a), such as Ecuadorian SMEs. Additionally, maintaining protection based exclusively on time makes S-DBR suitable for multi-product environments because expensive material safety stocks are not necessary for each product (Schragenheim & Dettmer, 2000a). Another positive factor is the simple structure of products in Ecuadorian SMEs, which does not require numerous assembly points that can create a barrier for S-DBR implementation (Schragenheim & Dettmer, 2000b).

With respect to the process variables, S-DBR still appears highly suitable for Ecuadorian SMEs. For example, the process pattern observed most frequently in Ecuadorian SMEs is the general flow shop. This material flow pattern is recommended for certain systems, such as S-DBR, where the CCR states must remain relatively stationary. Similarly, the presence of sequence-independent setup times is an incentive for S-DBR implementation because it is a system in which order sequencing should be constrained directly by the market (Schragenheim et al., 2009c). Moreover, considering the market as a unique constraint requires much less information relative to other traditional PPCs. In fact, empirical evidence indicates that S-DBR is a system in which control can be sustained based on visual management rather than sophisticated IT systems or highly skilled labour (Hwang et al., 2011), which is in good correspondence with Ecuadorian SMEs.

With respect to process variability, S-DBR, like other TOC production systems, tries to minimise planning complexity. As a result, S-DBR is indifferent to the presence of low or moderate processing time variability, such as those of Ecuadorian SMEs. Variability is buffered by the size of the time buffers established for each product family (E. Goldratt, 2006). Similarly, low or moderate inter-arrival time variability can be managed by the S-DBR mechanism, which proposes that orders be released ½ of a buffer time before an order is intended to be worked on in the CCR (Schragenheim, 2006). This mechanism retains a pre-shop pool in which orders wait according to the release time determined by the availability of the CCR.

In terms of volume demand variability, Ecuadorian SMEs can be considered moderately variable. The presence of this type of variability is still a risk because a sudden increase in the demand of certain products can lead to the emergence of temporary bottlenecks (Schragenheim et al., 2009c).

S-DBR is a PPC system that is better oriented to MTO environments (Jiun-Huei Lee et al., 2009) (Jun-Huei Lee et al., 2010) (Hwang et al., 2011). Several concepts, such as planned loads that set due dates based on a CCR's capacity or the inclusion of systems that continuously monitor the buffer consumption of orders, make S-DBR highly recommended for companies that pursue high DDP.

The high due date tightness characteristic of Ecuadorian SMEs may serve as a barrier for a system in which process variability is usually buffered by an increase in offered lead times. Some S-DBR applications in Ecuador have employed capacity reservation as an option to offer shorter DDs compared with the market standard (Schragenheim, 2006). However, this decision cannot be generalised due to the limited capacities exhibited by Ecuadorian SMEs. Finally, a positive point for the implementation of S-DBR in the Ecuadorian market is the stable allowance for DDs, which is reflected by low slack time variability. Therefore, the establishment of protective measures, such as increased lead times, will obviate frequent adjustments.

Table 3.7: Results f of the evaluation of the PPC approaches according to the Ecuadorian SMEs characterisation

Category	Dimension	Ecuadorian SMEs characterization	MRP	Kanban	DBR	WLC	S-DBR
Product characterisation	Level of customisation	Mushroom customisation	-3	-3	+9	+9	+9
	Product mix	Many products	+9	-9	+3	+9	+9
	Product structure	Simple products	+1	+9	+9	+9	+9
Process characteristics	Process pattern	Batch flow	-3	-3	+3	+9	+3
	Setup time correlation	Sequence independent setup times	+9	+9	+9	+9	+9
	Information characteristics	General/sparse/out-of-date/centralised information	-9	+9	+9	-9	+9
	Level of training	Low operator skill	-9	+9	+1	-9	+9
	Processing time variability	Moderate variability	-3	-3	-3	+9	+3
Market requirements	Order winner	Delivery reliability	-9	-9	+9	+9	+9
	Inter arrival time variability	Moderate	-3	-3	+9	+9	+3
	Volume demand variability	Moderate	-3	-3	-3	-3	-3
	Repetitiveness level	Highly repetitive	+9	+9	+9	+9	+9
	Due date tightness	High tightness	-9	-9	-3	-9	-9
	Due date allowance variability	Low variability	+3	+3	+9	+9	+9
	Total Score		**-20**	**+6**	**+60**	**+70**	**+78**

4

1. S-DBR implementation in four Ecuadorian SMEs. A case study research

This chapter explores the practical issues related to S-DBR implementation in four Ecuadorian SMEs through a case study. First, an explanation of the principles and mechanisms of the S-DBR methodology is presented.

4.1 Simplified Drum-Buffer-Rope Description

S-DBR is a TOC production application that was first proposed by Eli Schragenheim as an effective and less complicated version of traditional DBR. Designed for application in a broad range of manufacturing environments, S-DBR represents a suitable choice in situations for which DBR is too complicated (Schragenheim et al., 2009c).

One fundamental characteristic of S-DBR is that it always considers the market as a system constraint. Precisely, this critical emphasis on satisfying existing market demands provides S-DBR with a strong ability to fulfil higher levels of reliable due date performance (Jiun-Huei Lee et al., 2009). Considering the market as a unique constraint allows S-DBR to require only one buffer and to protect the customer delivery due dates. This single buffer, which is called the “shipping buffer”, can be defined as the average time from the release of raw materials at the beginning of the routing to the finished order reaching the shipping dock (Schragenheim & Dettmer, 2000c). The primary emphasis in this methodology is monitoring the accomplishment of the expected shipping buffer through the application of various concepts, such as the planned load or buffer management. The former is a method for setting due dates that establishes due date commitments based on the actual load in the capacity constrained resource (CCR). The latter is a system for managing order priorities that identifies which orders require additional decisions to achieve the expected due date.

Although S-DBR considers customer demands as permanent constraints, this does not limit the effectiveness of this system when an internal CCR is active (Schragenheim, 2006). In fact, the planned load concept, which is one of the pillar mechanisms of the methodology, has been designed to consider the workload of the internal CCR as part of the scheduling process.

4.1.1 Strategic and Tactic Tree

A strategic and tactic (S&T) tree is a TOC thinking process application designed to provide a graphical description of the business environment and communicate the sequence of actions required to achieve a specific business goal (Burton-Houle, 2001). By focusing on explaining how these changes should be implemented and justifying why they are required, an S&T tree becomes a complete and practical guide for the implementation of TOC organisational strategies (E. Goldratt, Goldratt, & Abramov, 2002).

An S&T tree is composed of a series of hierarchically structured levels, where the top level is reserved for the final mission statement and is considered the direction of the company (K. J. Watson, Blackstone, & Gardiner, 2007). The subsequent levels consist of the necessary activities required to achieve the mission statement. Every activity is composed of strategies and tactics, which are always presented in pairs. The strategy represents the state that the organisation wants to achieve and can be defined as the answer to the "what for" question. Tactics are the actions that the company must perform or avoid performing to implement the chosen strategy, representing the answer to the "how to" question. Figure 1 illustrates the S&T tree concept proposed by E. Goldratt et al. (2002).

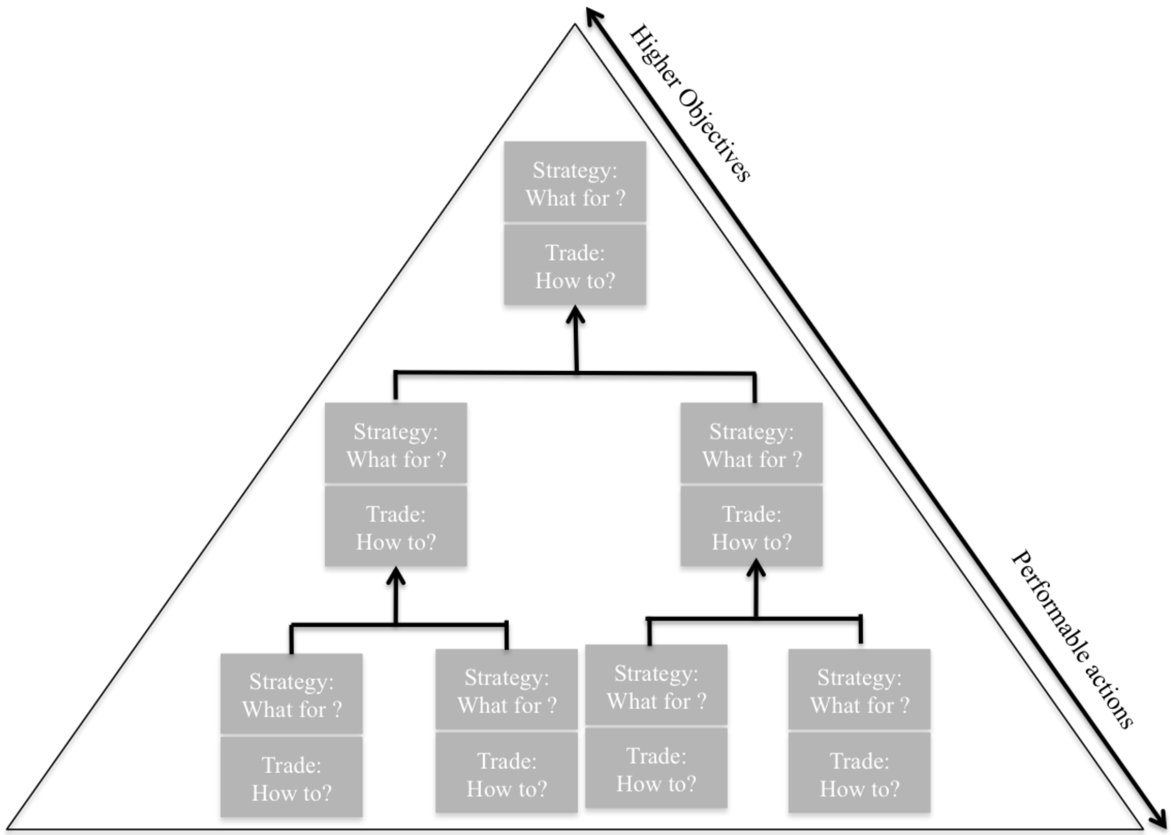


Figure 4.1: Goldratt's definition of a strategy and tactic tree.

E. Goldratt (2006) proposed a specific strategic and tactic tree for companies pursuing a highly reliable rapid response. The highest objective of this tree is presented as the viable vision (VV) and is described using the capacity of the company to sustainably make money at present and in the future. Two main pillars are proposed in the reliable rapid response S&T tree to achieve the viable vision: a) the development of a process offering highly reliable due dates and b) the establishment of a rapid response competitive edge. The elements proposed in the S&T tree for achieving a reliable due date have been considered in the literature as the required steps for the implementation of the S-DBR methodology (E. Goldratt, 2006).

4.1.2 Simplified Drum-Buffer-Rope mechanisms

The elements presented in figure 2 comprise the S-DBR S&T tree and incorporate all of the mechanisms proposed by the S-DBR methodology. An explanation of each of these mechanisms is presented in the following sections.

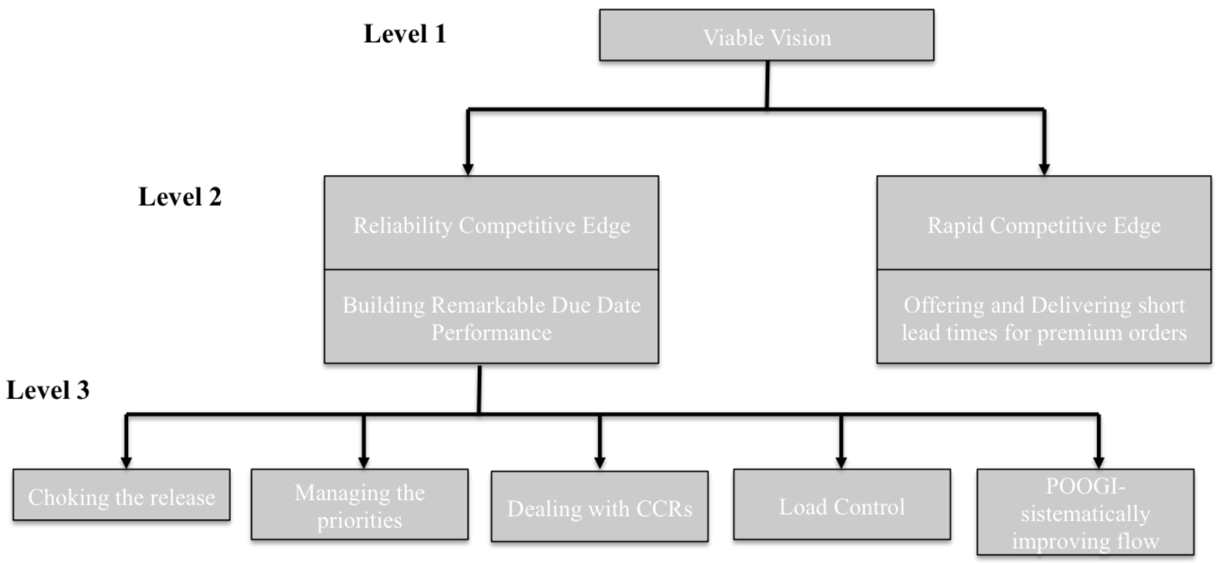


Figure 4.2: Strategic and Tactic tree for S-DBR implementation

Choking the release

The strategy associated with this step consists of populating the shop floor exclusively with orders scheduled for delivery within a pre-defined horizon. This strategy is sustained by setting production buffers at 50% of the actual production lead time. Numerous studies have found that this practice considerably reduces the amount of extra work required by each work centre, decreases the total flow time, improves the accuracy of the delivery dates, and clarifies the priorities on the shop floor (Cigolini, Perona, & Portioli, 1998) (Sabuncuoglu & Karapınar, 1999) (Corsten, Gössinger, & Wolf, 2005).

The S-DBR S&T tree requires that the persons related to releasing orders adhere to this procedure. The S-DBR S&T tree considers it necessary to configure a company's systems according to the established time buffers and disseminate the new procedures among the operational personnel.

Managing the Priorities

Every process is subjected to deviations originating from random events, such as machine breakdowns, quality issues or material shortages. Consequently, the personnel responsible for order control should utilise possible countermeasures to negate the effects of variations.

The absence of a priority system to regulate this type of initiative can lead to chaos, increasing the risk of late delivery and significantly disrupting the overall due date performance. In the S-DBR methodology, buffer management (BM) is the only priority system in charge of accomplishing an order's due date. This system provides the information required to support sensible decisions regarding the sequence of orders, which include expediting or postponing actions (H-H Wu & Liu, 2008) (Mabin & Balderstone, 2003). Violating BM principles by applying an alternative priority order system typically promotes local optimal behaviour and frequently only benefits only a few orders (E. M. Goldratt, Schragenheim, & Ptak, 2000).

Making the order buffer status visible increases the effectiveness of buffer management controls (E. Goldratt, 2006). Creating a board that shows the level of consumption of the buffer or colour tags located on the physical WIP assists in facilitating the recognition of buffer consumption on the shop floor.

Dealing with capacity-constrained results

S-DBR recognises that in many companies, capacity shortage can appear when proper demand variability generates peaks that overload the internal capacity of a company (Schragenheim et al., 2009c). The agile identification and effective elevation of the internal CCR are critical measures proposed by the S&T tree to prevent jeopardising the due date performance (E. Goldratt, 2006).

Various operational measures, such as programming the CCR without considering stops for lunch or breaks, sending orders to less effective but still useful work centres, reducing setup times, or adding an extra shift to the CCR, are suggested by the S-DBR S&T tree to effectively remove an identified CCR. An effective validation certifying that the CCR has been elevated provides the sales department with sufficient confidence to offer reliable due dates (E. Goldratt, 2006).

Load Control

The load control proposed by the S-DBR S&T tree prevents the CCR load from exceeding a previously established reasonable value for a company. Exceeding the load on the CCR can generate a dramatic increase in the lead time, severely affecting due date achievement (Hopp & Spearman, 2008). This mechanism can be described as the average time required to complete all work released to the shop floor that will pass through the CCR. By adding one-half of the shipping buffer to the front of the accumulated planned load, it is possible to offer delivery dates that the company will always meet (Schragenheim, 2006).

The sales department should be rigorously subordinated to the load control mechanism before offering order due dates to clients. However, this is challenging in some markets because clients are not prepared to wait a long time before receiving a delivery date. In these cases, companies should be capable of implementing flexible systems designed to offer delivery dates in just minutes (E. Goldratt, 2006).

In some cases, due date commitments based on planned loads are much shorter than standard quoted lead times, which represents a good opportunity to attract more clients. However, this practice eliminates the opportunity to offer shorter due dates at a higher price.

POOGI. Systematically improving flow

The application of continuous improvement tools without the support of a prioritising system can generate local improvements that cannot necessarily be translated into a global benefit for system (E. M. Goldratt & Cox, 2005) (Sadat, Carter, & Golden, 2013). POGGI is the essential element proposed by TOC through an S&T tree to prioritise the assignment of limited resources to those initiatives that have the highest impact on global performance.

POOGI considers the information provided by the buffer management to identify orders with unusual buffer consumption levels. Recording the causes of these disruptions allows for the identification of tasks that affect buffer consumption and guide future improvement tools (Cox III & Spencer, 1998). If the buffer consumption has penetrated beyond the remaining third of the time buffer – the red and black zone - all disruptions related to these orders should be classified as critical. POGGI proposes maintaining a reserved list for these issues that severely endanger order delivery times (E. Goldratt, 2006).

After the causes of disruptions are collected, they can be investigated using Pareto analysis. Every improvement initiative should be developed to strictly address the primary causes of delays, which are typically related to more frequent disruptions in the Pareto analysis. The application of this priority system leads to opportunities that improve the overall flow of a system. This practice maintains a working principle of TOC that provides a focus for continuous improvement (Rahman, 1998).

4.2 Case Study Research

A case study was chosen for this study to evaluate the S-DBR implementation in four selected Ecuadorian SMEs. The results are used to validate the conclusions of the previous chapter, which found S-DBR to be the most suitable system for Ecuadorian SMEs. Additionally, this section attempts to identify potential drawbacks of alternative methods, which enhances S-DBR system performance.

A case study can be described as an alternative research paradigm characterised by the combination of multiple disciplines that include both quantitative and qualitative methodologies (Meredith, 1998) (Roth, 2007). Typically, a case study involves multiple sources of evidence, such as direct observation, interviews, documents and other sources that consider temporal and contextual aspects related to the studied phenomenon (Leonard-Barton, 1990). Applying multiple sources of information allows researchers to obtain a better understanding of the contextual conditions under study compared with only quantitative analysis (Wacker, 1998) (Scudder & Hill, 1998).

According to Yin (2009), case studies can be classified as exploratory, descriptive or explanatory. The primary focus of descriptive case studies is illustrating events and their contexts. Explanatory studies aim to investigate causal relationships by linking events with their effects. Finally, exploratory case studies are applied from the beginning of the research and, by definition, in fields where theory is not clearly specified (Yin, 2009) (Mills, 2010).

An exploratory case study was chosen for this research because it is suitable for discovering how process and market characteristics of a company influence the implementation of S-DBR.

According to the methodology proposed by Stuart, McCutcheon, Handfield, McLachlin, and Samson (2002), the principles used to conduct a case study are as follows:

a) Definition of the research question
b) Instrument development
c) Data collection
d) Data analysis
e) Dissemination

In the following sections, each stage is briefly described and further developed for the presented study.

4.2.1 Definition of the case study research questions

Defining appropriate research questions contributes to establishing the boundaries of what is addressed by a case study (Yin, 2003). The questions should address a gap identified in the literature (Eisenhardt & Graebner, 2007), structured according to the selected strategy type (Yin,2003) and designed to obtain a full understanding of the real complexity of the selected events (Meredith, 1998).

The proposed questions focus on describing the effects of S-DBR implementation on the performance measures of a company. Additionally, the questions should contribute to understanding how the companies adapt the S-DBR methodology to the characteristics of Ecuadorian SMEs and how certain characteristics may hinder the implementation.

The research questions are formally stated as follows:

- **What is the impact of S-DBR implementation on SME operational performance?**

  The present study proposes a group of quantitative performance measures to assess S-DBR implementation. These measures are used in a case study to determine whether S-DBR implementation has positively influenced the performance of four Ecuadorian SMEs.

- **What are the implications of the Ecuadorian SME characteristics on the procedure for S-DBR implementation?**

  It is insufficient to evaluate a PPC by focusing on quantitative results alone. It is important to understand the differences in the S-DBR implementation process according to the characteristics of the companies in which this methodology is implemented. The case study provides qualitative evidence to determine the causes and effects of the differences in the four S-DBR implementations.

- **Which Ecuadorian SME characteristics may jeopardise S-DBR implementation?**

  This study examines experiences with implementing S-DBR to identify the characteristics that may jeopardise a successful implementation. These characteristics can be used to determine the requirements for enhanced S-DBR solutions that are perfectly suited to the Ecuadorian SME environment.

4.2.2 Company Selection

To answer the aforementioned research questions, a group of Ecuadorian SMEs were selected. The selection considered the different conditions that practitioners typically face during S-DBR implementation. Consequently, they broadly represent the practices typically adopted during a real-world implementation according to Ecuadorian SMEs.

A common issue associated with the application of a case study is the selection of an appropriate number of cases. Although theory does not state an ideal number of cases, many articles suggest a range between 4 and 10 as a suitable reference (Barratt, Choi, & Li, 2011) (Eisenhardt & Graebner, 2007). In this study, four companies from a group of Ecuadorian industries were considered according to the following inclusion criteria: they have (a) applied S-DBR as their PPC for more than two years and b) maintained historical data referenced to the operational performance from the S-DBR implementation up to the time of data collection for this study.

The Table 4.1 describes the selected companies. The table includes general data related to the product and process dimensions. The characteristics included in table 3.3 are based on the multi-dimensional classification proposed by B. L. MacCarthy and Fernandes (2000) for the design and selection of production planning and control systems.

Table 4.1: General information regarding the companies selected in the case study.

	Company A	Company B	Company C	Company D
Product	Plastic bags	Plastic bags	Medals	Offset printing
Sales	10 million	30 million	1 million	6 million
Number of employees	75	130	40	105
Production strategy	98% MTO-2% MTS	90% MTO-10% MTS	95% MTO-5% MTS	100% MTO
Repetitiveness level	Repetitive	Repetitive	Repetitive	75% are not repetitive
Order winner	Delivery	Quality	Delivery	Delivery/ Price
Product structure	Single-level products			
Number of families	25	4	3	15
Level of customisation	Standard components combined	Standard components combined	Standard components combined	Clients define design
Layout types	Functional layout			
Flow types	General flow shop			

All of the studied companies completed the implementation of the S-DBR methodology; therefore, it is expected that all of these companies satisfy the minimum requirements for S-DBR application. However, we considered it appropriate to determine the fit between the case study companies and the S-DBR methodology. This analysis prevents conclusions from being drawn for sites in which an initial suitability analysis would have identified the S-DBR implementation as infeasible.

The process characteristics included to determine the applicability of the S-DBR methodology were collected from the literature that describes the experiences of practitioners in companies that implemented S-DBR (Jun-Huei Lee et al., 2010) (Schragenheim, Dettmer, & PATTERSON, 2009a) (Hwang et al., 2011). The level of suitability presented in Table 4.2 was addressed by evaluating the similarity between the description of the process factors representing the "best fit" case for applying S-DBR and the proper characteristics of the four companies under evaluation. If the evidence presented for a company is in accordance with the "best fit" description, the process factor under evaluation is categorised as "best fit" in the "assessing the applicability" column. In contrast, if the characteristics of a company are not traditionally considered suitable for S-DBR implementation, the factor is categorised as "poor fit". Finally, if the data for the company show a process characteristic suitable for S-DBR implementation but exhibiting additional difficulties that must be overcome during the implementation process, the factor is characterised as "moderate fit".

Table 4.2 shows a reasonable alignment between the S-DBR methodology and the process characteristics of the four selected companies. In five of the six process characteristics, all of the companies were categorised as moderate or best fit for S-DBR implementation. Case C represents the only scenario in which a labour-constrained system provides an additional challenge during S-DBR implementation. Similarly, in cases C and D, the non-depreciable dependence of the setup times on order sequencing can generate additional S-DBR implementation complexity. All of these cases are analysed in detail in the case analysis section. Despite these exceptions, the analysis shows a high level of fit between the companies selected and the S-DBR requirements. These results provide evidence that the selected companies are appropriate for evaluating the performance improvements due to S-DBR implementatio

Table 4.2: Applicability of S-DBR at the four companies selected for the case study

Process Characteristics	S-DBR "Best Fit" Description	Case A	Assessing Applicability	Case B	Assessing Applicability	Case C	Assessing Applicability	Case D	Assessing Applicability	Case E	Assessing Applicability
Manufacturing process time longitude	Processing time is considerably shorter than the production buffer, allowing order sequence evaluation to easily accommodate changing conditions on the shop floor.	Touch time <10%	Best fit	Touch time <10%	Best fit	Touch time <10%	Best fit	Touch time <10%	Best fit	Touch time <10%	Best fit
Sequence-independent setups	Releasing orders immediately following market conditions is possible only when a work order on the CCR does not adversely affect its capacity.	Sequence moderately affects the CCR capacity	Medium fit	Sequence-independent setups	Best fit	Sequence-independent setups	Best fit	Sequence moderately affects the CCR capacity	Medium fit	Sequence-independent setups	Best fit
Labour-constrained systems	If the operators are considered the CCR, assessing the expected CCR capacity is more difficult.	Machine-constrained	Best fit	Machine-constrained	Best fit	Labour-constrained	Poor fit	Machine-constrained	Best fit	Machine-constrained	Best fit
Number of operations on the CCR	If the same order returns to the CCR more than once, the flow system is considered a re-entrant flow. This characteristic brings additional complexity to the sequencing, requiring a longer production buffer.	One operation on the CCR	Best fit	One operation on the CCR	Best fit	One operation on the CCR	Best fit	One operation on the CCR	Best fit	One operation on the CCR	Best fit
Number of CCRs	One effect of utilising more than one CCR in the routing is the loss of focus-generating disruptions.	One CCR	Best fit	One CCR	Best fit	One CCR	Best fit	Once CCR	Best fit	One CCR	Best fit
Wandering bottlenecks	The application of excessively large batches, frequent changes in the product mix or the application of a long maintenance period result in the creation of a new bottleneck.	Stationary CCR	Best fit	Stationary CCR	Best fit	Stationary CCR	Best fit	Stationary CCR	Best fit	Stationary CCR	Best fit

4.2.3 Performance Measures for S-DBR

This section addresses the identification appropriate measures by analysing the performance indicators previously applied in simulations or real implementations of TOC production applications. An effort was made to review the DBR and S-DBR academic literature since 2000 to identify previously used performance measures. The previously used performance measures can be classified into four groups: time-related, dependability, shop-related and finance-related. Table 5 documents the performance measures encountered in each of the four categories identified in the literature review.

The time-related factor that is most frequently included in the TOC production application literature is the lead time (Atwater & Chakravorty, 2002) (Patti, Watson, & Blackstone Jr, 2008) (Horng-Huei Wu, Chen, Tsai, & Yang, 2010) (Georgiadis & Politou, 2013) (Qiao & Wu, 2013). Described as the time between the release of a job at the beginning of the routing and the job reaching the end of the process, this measure is considered to be an appropriate indicator of the amount of work in progress on a particular route. This well-established relationship between WIP and lead time explains why several previous studies did not consider both measures to be necessary.

Table 4.3: Performance measures used in DBR and S-DBR previous studies

Category	Measures	Examples of authors including this measure
Time-related	Mean lead time	Chang and Huang (2011), Hwang et al. (2011), Patroklos and Alexandra (2013) Fei and Qidi (2013), Wu et. al (2010), Betterton and Cox (2009), Patti et. al (2008) Wattson and Patti (2008), Sirikrai and Yenradee (2006), Umble et al. (2006), Steele et al. (2005) Chakravorty and Atwater (2005), Atwater and Chakravorty (2002), Gupta et al. (2002) Corbett and Csillag (2001),Kadipasaoglu et al. (2000)
	Standard deviation of lead time	Wattson and Patti (2008),Fei and Qidi (2013)
	Shop floor queue Time	Betterton and Cox (2009),Kadipasaoglu et al. (2000)
Dependability	Mear earliness	Chang and Huang (2011), Chakravorty (2001)
	Due date performance	Hwang et al. (2011),Sirikrai and Yenradee (2006), Umble et al. (2006),Chakravorty and Atwater (2005) Atwater and Chakravorty (2002), Chakravorty (2001),Gupta et al. (2002),Corbett and Csillag (2001) Jodlbauer and Huber (2008)
	Mean tardiness	Gonzalez et al. (2010),Sirikrai and Yenradee (2006),Chakravorty and Atwater (2005), Chakravorty (2001)
	Maximun tardiness	Gonzalez et al. (2010)

Shop load measures	Utilisation CCR	Hwang et al. (2011),Fei and Qidi (2013),Sirikrai and Yenradee (2006),Steele et al. (2005)
	Resource utilisation	Gupta et al. (2002),Kadipasaoglu et al. (2000)
	Location of the CCR	Kadipasaoglu et al. (2000)
	CCR production rate	Patroklos and Alexandra (2013)
	Daily production rate	Wu et al. (2010),Patti et. al (2008),Wattson and Patti (2008),Sirikrai and Yenradee (2006)
	Production capacity	Umble et al. (2006),Corbett and Csillag (2001)
Financial-related measures	Throughput	Chang and Huang (2011),Hwang et al. (2011), Koh and Bulfin (2004),Atwater and Chakravorty (2002) Gupta et al. (2002)
	Operating expenses	Koh and Bulfin (2004),Gupta et al. (2002)
	Sales volume	Umble et al. (2006),Corbett and Csillag (2001)
	Profitability	Umble et al. (2006),Koh and Bulfin (2004)
	Inventory cost	Chang and Huang (2011),Chakravorty (2001)

Numerous studies reporting TOC production applications have registered a substantial lead time reduction (Umble, Umble, & Murakami, 2006) (Corbett & Csillag, 2001) (Hwang et al., 2011), which can be explained as a consequence of the TOC principle that limits the release of orders to the shop floor in accordance with a constraint schedule. Additionally, an many simulations use the lead time as the primary measure of the effectiveness of DBR procedures under different operational environments. For example, K. Watson and Patti (2008) explored DBR applications considering unbalanced lines facing unplanned machine downtimes. Similarly, Betterton and Cox (2009) treated the lead time as a performance measure to evaluate the impact of DBR implementation on a single product serial production line. Finally, other studies have considered the lead time as a critical measure for comparing the performance of DBR and other PPC systems, such as CONWIP (S.-G. Koh & Bulfin, 2004), Kanban (K. Watson & Patti, 2008) and MRP (Jodlbauer & Huber, 2008).

DBR and S-DBR are TOC production applications that emphasise providing highly reliable due date performance. Consequently, most of the literature presents dependability measures that evaluate attempts to improve DDP. Described as the percentage of orders that are served within the quoted lead time, the service level has been selected by many authors as the primary indicator for evaluating on-time delivery performance. Most case studies have demonstrated a significant increment in service level, achieving a DDP that exceeds 90% (Hwang et al., 2011) (Umble et al., 2006) (Corbett & Csillag, 2001). Various measures, such as the mean lateness, mean tardiness or due date slack time, are additional dependability measures that have been included in numerous studies (Chakravorty, 2001) (Chakravorty & Atwater, 2005) (Gonzalez-R, Framinan, & Ruiz-Usano, 2010).

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Concurrent with the TOC principle of obtaining the maximum constraint utilisation (Rahman, 1998), capacity measures are considered primary interests in the TOC implementation literature. The capacity measures utilised in previous studies can be categorised into two groups: shop load-related measures and production capacity indicators. CCR utilisation is a shop load-related measure frequently used to explore the effects of production scheduling methods on CCR exploitation (M. Gupta et al., 2002). The literature reports a consistent increasing exceeding 80% in CCR utilisation after TOC implementation (Steele* et al., 2005) (Sirikrai & Yenradee, 2006). In some studies, resource utilisation was found to become an explanatory variable rather than a performance measure. For example, Kadipasaoglu et al. (2000) investigated the effect of CCR utilisation and its location on operational performance measures, including flow time, work in process and waiting time.

Additionally, many authors have adopted measures with a primary emphasis on evaluating the impact of TOC implementation on the production capacity of a system. Numerous real application case studies found an significant increase in production capacity without an increase in investment (Hwang et al., 2011) (Umble et al., 2006). This improvement can be explained by a better use of a system’s inherent capacity, which can be achieved by focusing solely on orders that must be filled within a pre-defined horizon.

TOC describes the final goal of a company as its ability to make money now and in the future (E. Goldratt et al., 2002). Although financial measures are typically considered proper indicators for evaluating the performance of a system toward this goal (Rahman, 1998), TOC proposes a group of measures that allow individuals to know how their activities on the shop floor directly affect these financial indicators. Throughput, inventory and operating expenses are the operational measures proposed in the TOC literature that are directly related to the global financial measures of a particular company.

Throughput indicates the rate at which a system generates money; it is calculated as the total sales minus the variable costs. Meanwhile, inventory represents all money invested in, e.g., raw material, work in process, and the inventory of finished goods, which includes various capital goods (equipment, buildings and furnishings). Finally, operating expenses represent all money used by the system to convert inventory into throughput. In some cases, a lack of information necessitates the inclusion of only a specific type of expenditure for calculating these measures. For example, S.-G. Koh and Bulfin (2004) used only the holding cost per unit time to calculate the operating expenses for a comparison of DBR and CONWIP.

In addition, some studies have adopted other performance indexes that include monetary values. For example Y.-C. Chang and Huang (2011) proposed measures related to the accomplishment of due dates based on the dollar value of products. These measures are called the throughput dollar day, which is defined as the sum of the value of orders multiplied by the number of days that orders are late, and the inventory dollar day, which is defined as the sum of the WIP value multiplied by the number of days since the WIP entered the plant. The high interdependence between these type of measures and the profit goal of a company makes its inclusion important for assessing the impact of operational decisions on a company's global performance (M. Gupta et al., 2002).

The discussion above demonstrates how some performance measures have been used in several simulations and case studies to determine the effects of TOC production applications on operational and financial performance. Some of these measures are included in this study to evaluate the effects of the S-DBR implementation process design on the operational performance considering the necessary refinements originated by the product or process characteristics of a company.

Based on the four previously defined categories, the performance measures included in this study are as follows:

Time-related measure: Mean lead time (MLT)

Dependability measure: The percentage of orders served within the quoted lead time (service level)

Shop-load measures: Capacity constrained resource utilisation and production capacity

No finance-related measures were included in this study because most of the companies studied refused to provide this type of information.

4.2.4 The Instrument Development

The second step in the case study research process is the design of a tool that is capable of capturing the data required for the analysis. This instrument is called the research protocol and is considered the main document in case-based research (Stuart et al., 2002). This instrument includes general company information, such as product descriptions, the number of employees, product volume, and additional information that provides the researcher with a clear understanding of the selected sites (Choudhari, Adil, Ananthakumar, 2012). Additionally, the protocol is the instrument that organises the questions used by the investigator during interviews and ensures that all evidence is conveniently documented (Yin, 2009).

In this study, the research instrument includes the literature interpretation of the S-DBR implementation process design. In this case, it is based on the S-DBR S&T tree proposed by E. Goldratt (2006) as a reference for S-DBR implementation. This widely accepted guide has been applied by most S-DBR practitioners during implementations and is considered to be a reference for the four companies included in this study. This document was used as a guide during the interviews and data collection for the four companies included in this study.

4.2.5 Data Collection

Each interview lasted approximately 90 minutes and included an assessment of the extent of implementation according to the established protocol. During the interview, information was collected regarding motivations for a total or partial implementation of the strategies proposed in the reference protocol. Additionally, several documents, such as operational reports and auditing results, were provided. Finally, visits to the shop floor and interactions with the operative personnel provided the researchers with a feel for the effectiveness of the system during day-to-day activities. For additional clarification, telephone or e-mail communication with those in charge of the PPCs was conducted.

The information utilised in this research was primarily collected through semi-structured interviews. The interviews focused on the persons who were part of the implementation team or are responsible for sustaining the methodology.

Before the data collection, a pilot study was conducted in one of the five studied companies. This company was selected based on its level of experience with the application of the S-DBR methodology and its predisposition for providing information. In this case, the head of the TOC implementation provided us with the necessary feedback to refine our protocol instrument and prepare us for the interviews with the other companies.

Each interview lasted approximately 90 minutes and focused on the motivations for the null or partial implementation of the strategies proposed in the S-DBR S&T tree. Other sources of evidence, such as the operational or financial reports, quantitatively supported the results of the interviews.

4.2.6 Data Analysis

The obtained findings support the explanation of why some cases achieved certain results and others do not.

Once the observations and recording of evidence were completed, the challenge arose of obtaining a sensible interpretation out of the chaos induced by the volume and diversity of the available data (Stuart et al., 2002).

The literature proposes different approaches for the analytic manipulation of data. Among the principal choices are pattern-matching, explanation-building, time series analysis, logic models, within-case analysis and cross-case analysis (Yin,2003). These techniques are focused on becoming familiar with the information collected and building knowledge that allows an explanatory theory to be developed.

In this study, the inclusion of multiple cases necessitates the application of within- and cross-case analyses. The former provides the researcher with a contextual background of the studied units. Additionally, this analysis results in a detailed description of the S-DBR implementation process and a report of the causes that motivated divergences with respect to the

S-DBR S&T tree. A cross-case analysis looks for within-case similarities and inter-group differences, allowing conclusions to be drawn based on multiple perspectives, not just initial impressions (Stuart et al., 2002) (Yin, 2009). The obtained findings will support the logic that explains why one group of cases achieved certain results, whereas others did not.

Multiple graphics will be applied to compare and analyse the findings regarding the S-DBR implementation process and its effects on the operational performance of each of the four studied companies.

4.2.7 Within-case Analysis

Each analysis begins with a presentation that includes the company background. Posteriorly, decisions regarding the S-DBR implementation based on the process characteristics of a company or preferences of the top management are discussed. This discussion is presented alongside the five principles established by the S-DBR S&T tree.

Finally, the effects on the performance measures that are directly associated with the S-DBR implementation process are identified for each case. This information serves as a precursor for the cross-case analysis, which will explore how the different configurations and contextual factors affect the operational performance dimensions.

General Description for Case A

Company A manufactures plastic rolls and bags for retail and industrial applications. The industrial segment characterised by the requirement of highly reliable due dates represents nearly 80% of sales. Consequently, achieving high delivery reliability is a competitive priority.

Composed of 75 employees and nearly 10 million dollars per year in sales, company A can be categorised as an medium Ecuadorian enterprise.

Operations at company A are distributed according to a functional layout, and the product families flow in accordance with a general flow shop. Thus, the flow follows usual maintained pre-established routings for each family with exceptional variations.

Most of the products elaborated by company A are repetitive. Customisation in the product design is limited to special orders that represent no more than 5% of sales. In the case of printed rolls or bags, the customisation is left to the printing process, which is one of the later stages in the production system.

Company A is characterised by an intensive use of resources. Capacity increases are typically obtained by the replacement or acquisition of equipment. This managerial tendency of replacing or increasing the number of machines has resulted in little interest in developing continuous improvement initiatives. Programs such as 5S or statistical process control (SPC) have failed to produce benefits because of the lack of top management commitment to supporting these types of initiatives.

S-DBR implementation in case A

Element 1: Choking the release in case A

Prior to S-DBR, company A did not exhibit any restrictions with respect to releasing orders. The plant manager determined the release date based on a simple rule: orders should be released as soon as possible to achieve the due date. However, the due date performance did not achieve the expected results. The formation of increasing queues before machines significantly affected the lead times and consequently the service level of the company.

The main rule used to prioritise orders in the queues was typically the increase in productivity. Operators were motivated through the implementation of bonuses that were paid when the production goal was exceeded. Consequently, operators prioritised high-volume orders or selected a sequence that minimised setup times without considering the market requirements.

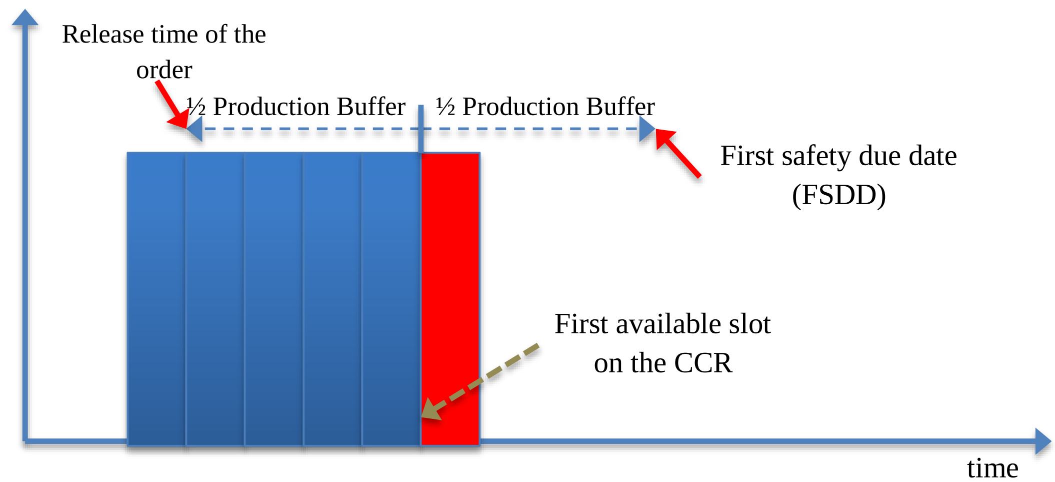
A group of orders was frequently finished too many days in advance, while the most urgent orders were trapped in the middle of the work in process. Generally, the company was inundated with orders that clients were indifferent to receiving before the deadline, whereas others suffered delivery delays. The final result was poor service performance that never exceeded 65%.

Consequently, in case A, the S-DBR implementation initially required the total elimination of the productivity incentive program. This program was replaced to allow the system to achieve highly reliable due dates.

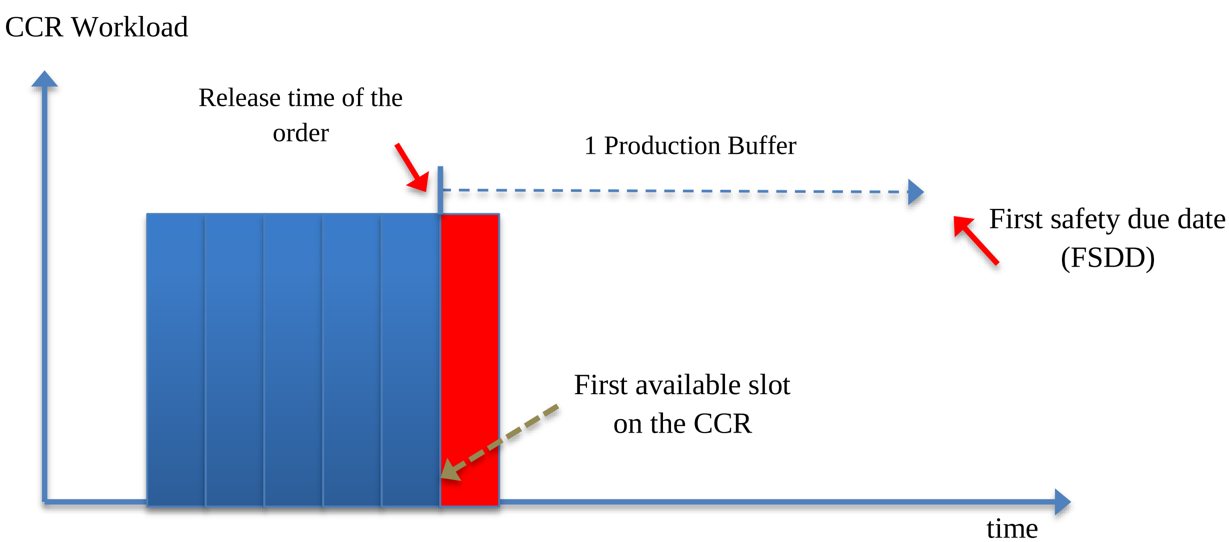
Originally, the mechanism for setting due dates was the one traditionally suggested by the S&T tree, wherein the first safety due date is set by adding one half of the shipping buffer to the first available slot in the planned load of the CCR, which can be described as an estimate of the time between the release of materials and the order completion (Schragenheim et al., 2009c). This mechanism assumes that the CCR is located at the midpoint of the routing. Consequently, an order will require only half of the production buffer to proceed through half of the routing from the CCR to the shipping dock.

However, in case A, the CCR was located in the first stage of the routing. In this case, assigning 1/2 of the shipping buffer to proceed through the first half of the routing was a waste because there was no previous CCR operation. The consequence of this mismatch was offering overly optimistic due dates because only ½ of the shipping buffer was reserved to pass through the entire routing.

During the first weeks of implementation in case A and not considering the real location of the CCR, poor due date performance that never exceeded 75% was generated. This issue was resolved by making a minor modification in the traditional mechanism proposed by Le et al. (2010) that is presented in figure 4.3. As a result, the due date was determined by adding an entire shipping buffer period to the first available slot in the planned load of the CCR as is presented in figure 4.3(b). This modification provided orders with an entire production buffer period to pass through all of the routing between the CCR and the shipping dock. The results of this modification were substantial, increasing the service level from approximately 75% to 90% in only one week.



(a)



(b)

Figure 4.3: Mechanisms for due date estimation

(a)Mechanism proposed by S-DBR for establishing the FSDD and the release time based on the CCR is located at the middle of the routing (b) Alternative method applied at case A considering the CCR was the first operation at the routing.

The result presented in figure 4.4 was an evident improvement, with a 92% service level at the end of the first year of implementation.

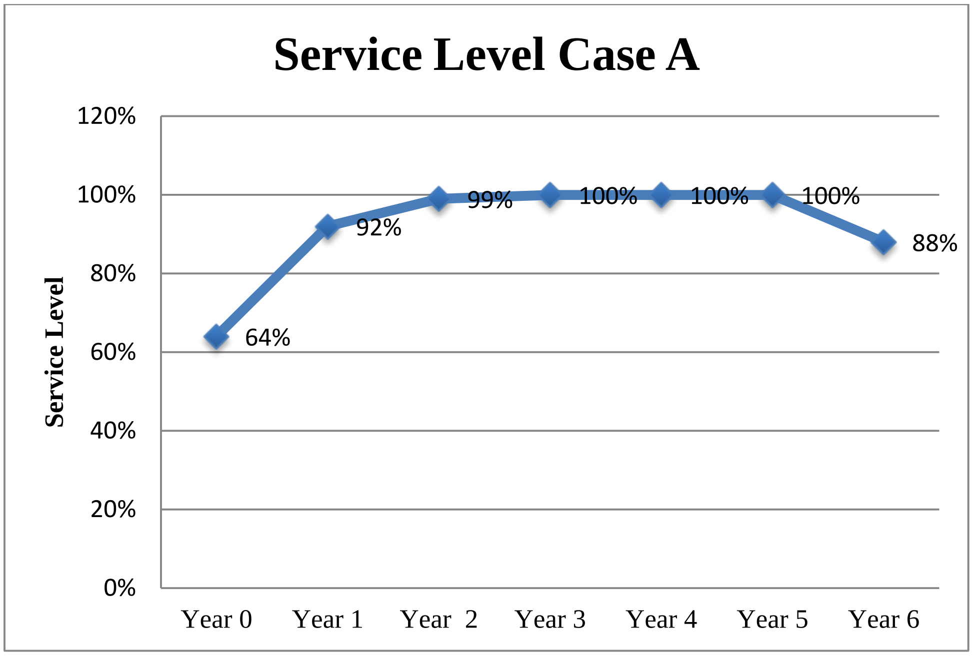


Figure 4.4: Service level in case A

Element 2: Managing the priorities at case A

Before S-DBR, the priority system in company A was based on increased productivity, which significantly affected the service level performance. As part of the S-DBR implementation, company A decided to implement buffer management (BM) as the only priority system at the plant.

Through the application of specialised software, the company captured and processed the BM information. The results were presented through traditional reports and displayed to the workers using electronic means, such as LCD screens and computers allocated strategically on the shop floor. These means provided real-time feedback, empowering operators to take immediate action on the situations presented on the shop floor. The observed results were in accordance with those proposed by such authors as Cox (1998), who considered BM to be a supporting tool for making shop floor decisions.

In addition to the electronic means, colour tags were adhered to the WIP containers, providing buffer status information without requiring computer queries or LCD screens. This notorious simplicity of the BM methodology facilitated the translation to simple visual controls.

Element 3: Addressing capacity-constrained resources in case A

In some cases, political, technical or market conditions can generate a CCR re-allocation (E. M. Goldratt, 1990). Consequently, the establishment of systems that allow for the identification of emerging CCRs is fundamental for a successful S-DBR implementation. Any proposed system should support actions that effectively increase capacity while not making internal resources a limitation to achieve high DDP (E. Goldratt, 2006).

At company A, workload registration was implemented for the considered critical resources. Through the application of specialised software, it was possible to determine how the workstations were utilised in real-time, readily identifying the emergence of new CCRs. However, this information was not part of any formal procedure for monitoring the internal resources. The results were privately managed by the production manager and rarely shared to provide support for the operational decisions. This can be explained by the company's lack of interest in obtaining internal information to prevent or remediate the emergence of new CCRs. Instead, an intensive acquisition program focused on new and more efficient machinery was used. Although the measure initially appeared to be effective, the financial limitations significantly delayed acquisitions, which affected the protection against the appearance of new CCRs.

For example, printers were originally considered sub-utilised machines; however, due to a change in the product mix, they became the new CCR of the process. According to figure 4.5, the utilisation of printers increased from 50% to nearly 70% after one year and from 80% to 90% from year 4 to year 7, respectively.

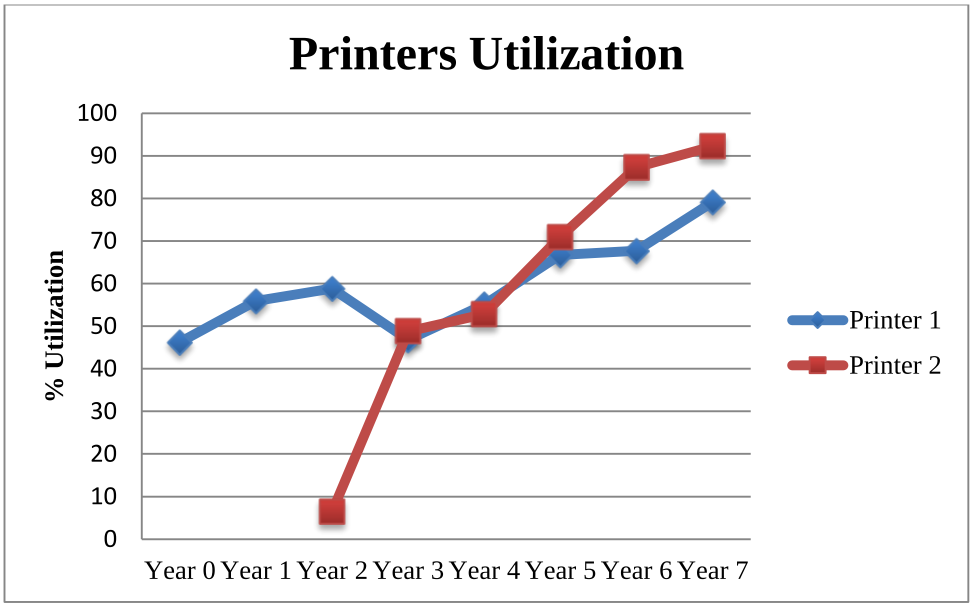


Figure 4.5: Printer utilisation in case A

This change was initially perceived as being favourable based on the increased prices of printer products. However, the lack of preparation generated significant consequences for the company's performance.

Although the data revealed a significant and consistent increase in printer utilisation, limited actions were aimed to expose the additional capacity. Company A considers an increase in capacity necessary through an intensive equipment acquisition program. It was well known that once the new equipment was implemented, the company did not wait to confirm its new capability before rolling out reliable offers. The trial time suggested by the S&T tree as being equivalent to a production buffer time was considered irrelevant for the company. Despite the lack of serious consequences identified in this case, not providing the necessary trial time before giving the sales department the green light may significantly affect DDP, especially in highly variable environments.

This managerial tendency of replacing or increasing the number of machines to mitigate the lack of capacity has resulted in little interest in developing continuous improvement initiatives. Programs such as 5S, statistical process control (SPC), and total productive maintenance (TPM) have failed to produce benefits because of the lack of top management commitment to supporting these types of initiatives. The primary reason for this lack of commitment is the top management's lack of knowledge regarding the benefits of such continuous improvement initiatives. Additionally, there is a very deeply rooted belief that any improvement at non-constrained workstations is a waste of resources.

Element 4: Load control in case A

Considering the market as the major system constraint is one of the main differences between S-DBR and its predecessor, DBR (Schragenheim & Dettmer, 2000b). Applying this principle shifts the focus from the capacity exploitation of the CCR to protecting the market from unreliable delivery dates.

Consequently, scheduling the CCR is no longer the planning priority. In this case, monitoring the CCR only provides a good estimation of an order's lead time, allowing unreal due date commitments to be avoided according to the planned load. However, this basic mechanism is based on the S-DBR assumption that the operation touch time is as small as a 10% of the lead time (E. Goldratt, 2006). In this case, any change in the sequence will have a minimal influence on the buffer consumption, facilitating work by uniquely considering the sequence directly required by the market. This final notion is the primary assumption of the S-DBR methodology.

However, company A experienced some difficulties in the application of this principle. The high processing time variability within product families and the influence of sequencing on the CCR capacity significantly reduced its flexibility.

The first problem resulted from originally considering all products within the same family, maintaining an average CCR processing time. This practice operates on the underlying assumption that the touch time is very short relative to the lead time. Consequently, small changes in processing time estimates within the same family do not adversely affect a CCR's capacity and the estimated due date.

However, this solution was not suitable for two families of products in company A, which have lead times with a coefficient of variation (CV) exceeding one. For these products, the presence of large-volume orders generated a discrepancy between the estimated and the real CCR workloads, where the due dates resulting from the planned load mechanism differed significantly from reality. The final result was overly optimistic due dates that were often unmet. The solution was to establish different CCR processing times for products with highly variable processing times in a family. Positive results were obtained almost immediately; the percentage of late orders decreased from 25% to 10% in less than one month.

With respect to the influence of sequencing on the capacity, a suggested order arrangement must be proposed to minimise the impact of sequencing. Any re-arrangement in sequencing is always subordinated to the BM priorities. Therefore, orders can be re-arranged according to the sequence that minimises the setup times within each range of colours.

Element 5: Process of on-going improvement (POOGI) in case A

According to the TOC philosophy, improvement initiatives are valuable if they result in not only better local KPIs but also improving a company's global performance (Rahman, 1998). POOGI is the methodology proposed by TOC for the establishment of continuous improvement initiatives (Cox III & Spencer, 1998) (Sullivan, Reid, & Cartier, 2007). This methodology contains three focused steps: (1) determining the causes of generated orders that consumed more than 2/3 of their production buffer (red-black orders), (2) conducting a Pareto analysis of the determined causes, and (3) developing continuous improvement projects considering the main causes of disruptions that endanger on-time delivery.

Although company A accomplished the two first steps, there was a notorious lack of alternatives aimed to mitigate the principal causes of disruptions in the process. The case of the printers provides a clear example of a lack of initiative taken to mitigate a clear increase in lead times (Fig. 6).

The argument above is sufficient to categorise company A as a reactive case in which improvement measures are only app0lied when the problems have seriously affected the company's performance. Consequently, the long-term results, such as the decreased service level in year 6, should be analysed based on the previous statement rather than directly related to the S-DBR methodology.

S-DBR implementation in Case B

Element 1: Choking the release in case B

Prior to the S-DBR implementation, company B maintained an immediate release strategy in which due dates were established without considering the status of the shop floor in any case. Because the plant has a high level of utilisation, the production manager considered releasing orders as soon as they achieved a good practice. This practice was considered a measure of reducing the probability of delays in the production process. However, this practice only resulted in increasing the amount of work in the process and lead times, which in turn made it more difficult to determine the correct priority of orders on the shop floor. This complication was a result of releasing orders according to due dates that did not consider the real state of the shop floor, which is equivalent to releasing orders assuming that the plant maintains infinite capacity. As a result, the immediate release of orders significantly reduced the service level, which never exceeded 75%. Once released, the orders on the shop floor flowed according to the FIFO rule; however, the sequence was continuously modified depending on the inclusion of new orders and clients' complaints.

After S-DBR was implemented, the primary positive consequence of releasing orders in accordance with the CCR availability was a clear shop floor, which reduced the lead times. Through the application of this measure alone, the figure 4.6 presents that it was possible to reduce the original lead time by half, increasing the service level from 74% to 87% during the first year of implementation.

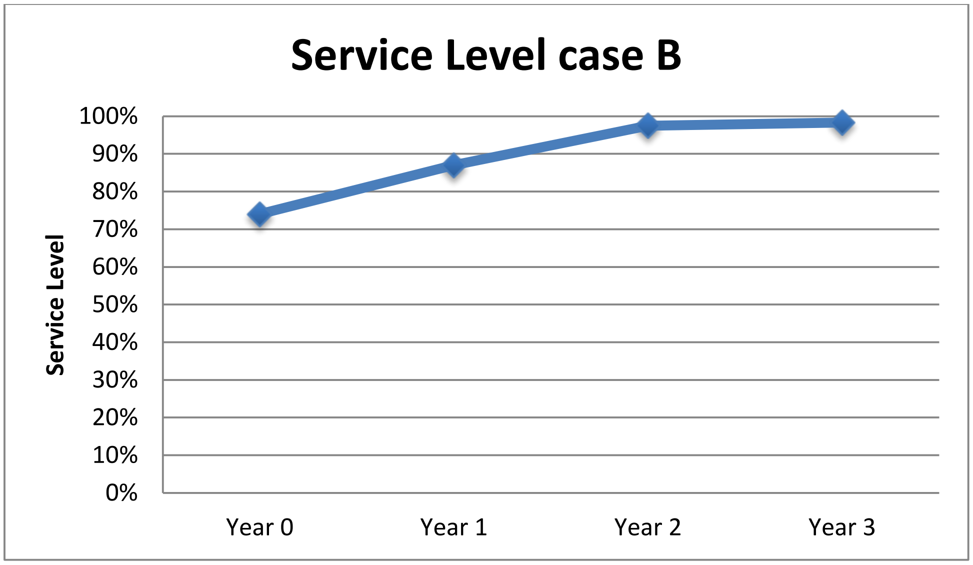


Figure 4.6: Service Level for Case B

The explanation of this result was absolutely consistent with the theory. The reduced congestion significantly increased the flexibility and clarified priorities, making additional capacity that was previously hidden available for the most critical resources.

Element 2: Managing the priorities in case B

In case B, after S-DBR implementation, specialised software provides necessary reports to show an order's buffer status in nearly real-time. Useful and friendly interfaces facilitate access to this information through the use of computers located in strategic sites on the shop floor. These computers provide real-time feedback about the buffer order status, empowering operators to take immediate action on problems as they occur. Previously, all operators were trained to follow the priority system and provide a warning when problems affecting the schedule fulfilment were recognised.

Company B has been characterised by discipline. Its operators are absolutely convinced of the benefits provided by the S-DBR methodology and strictly follow the priority provided by the BM management. However, not until the third year of implementation was it possible to achieve a service level exceeding 99%. The reason is related to the high level of utilisation, which exceeded 100% in the peak season. In this case, overtime or outsourcing was necessary.

However, case B is a clear example of how strictly following the order priority allows a company to achieve a proper service level, even maintaining a high level of utilisation. After S-DBR implementation, decision-making power during execution was given to the shop floor personnel and supported by the BM criteria. Despite initial scepticism, figure 4.7 presents that an increasing service level has been maintained, and the lead times have been reduced.

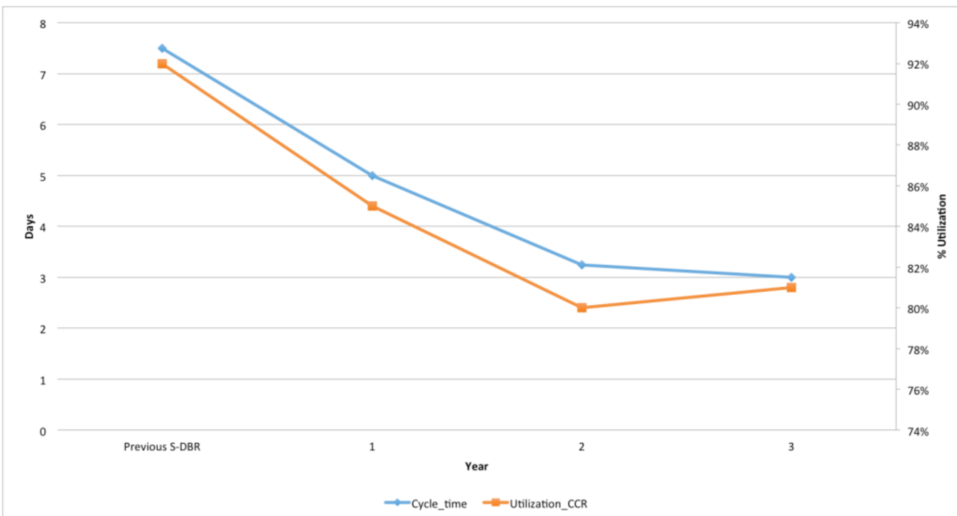


Figure 4.7: Lead time and CCR utilisation in case B

Element 3: Addressing capacity-constrained results in case B

Case B formally established a procedure for monitoring the workload of the stations considered vulnerable to becoming CCRs. This procedure is supported by weekly operational meetings that act as a formal channel for proposing alternatives aimed to increase the capacity of CCRs. These initiatives include the application of continuous improvement tools, such as Ishikawa diagrams, Pareto charts, brainstorming and the 5 Why's technique. Most of these techniques are applied during the root cause identification phase. The efficacy with respect to the application of these initiatives can be observed in such results as the reduction of the lead time from 8 to 3 days (Fig. 8). All of these improvements were achieved without any inversion beyond the minimum required for the exploitation of the CCRs.

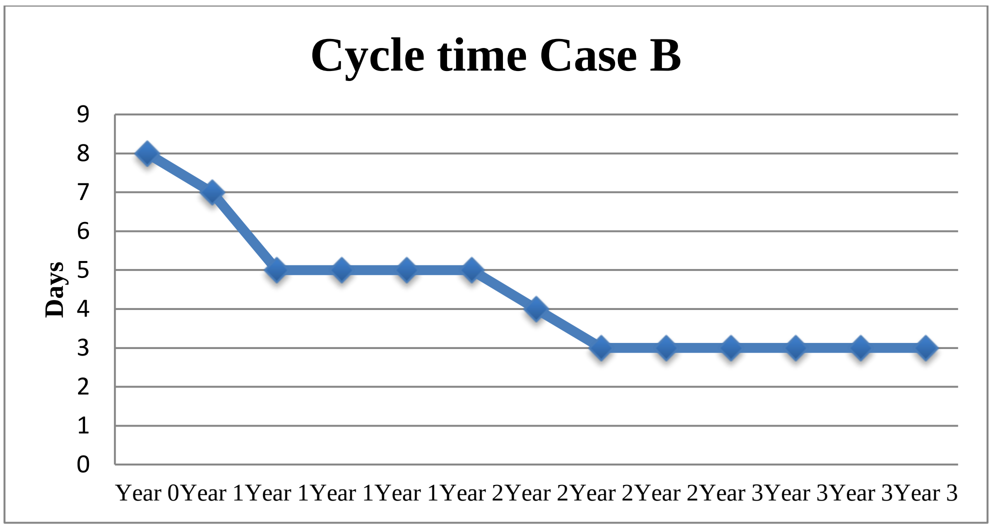


Figure 4.8: Lead time in case B

The S&T tree states that it is necessary to establish a trial period of one month after applying actions to evaluate the CCR capacity (E. Goldratt, 2006). This period is required to ensure that the due dates offered can be sustained over longer periods. However, this measure was not applied in company B. In this case, the green light was given to the sales department to quote due dates as soon as the improvement measures were implemented in the CCR.

Element 4: Load control in case B

In case B, the CCR is located approximately at the middle of the routing. Consequently, due dates are established considering the standard practice of adding ½ of the buffer time to the first available slot in the CCR. The primary result was a clear shop floor, which improved the flow of products and thereby reduced lead times. During the first six months, the clear shop floor reduced lead times by nearly 38%, from 8 to 5 days (Fig. 7).

The service level performance in case B shows the effectiveness of the load control, even in cases with high CCR utilisation (Fig. 8), which resulted from the procedure for establishing due dates and the achievement of BM priorities.

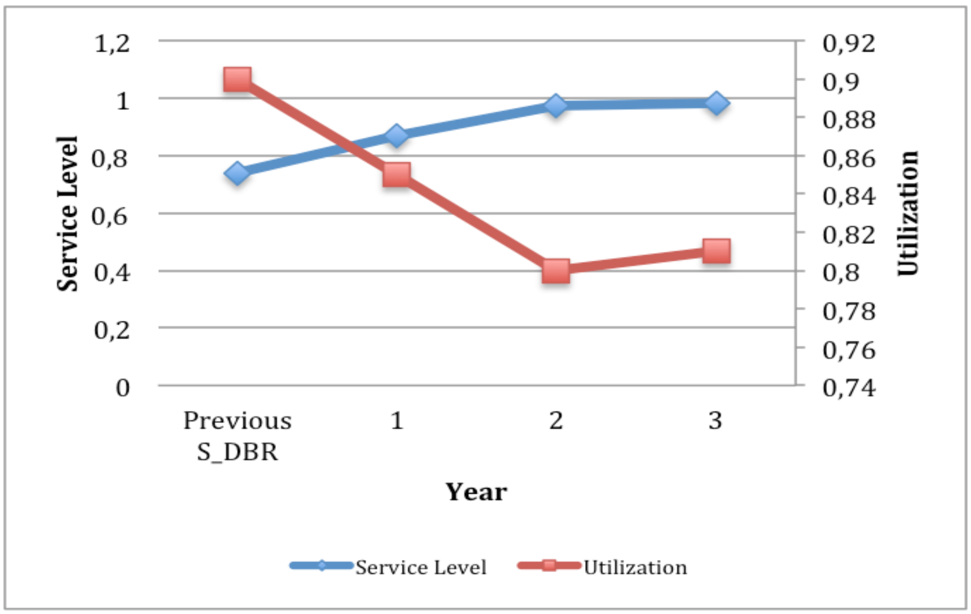


Figure 4.9: Service level and utilisation in Case B

Element 5: Process of on-going improvement (POOGI) in case B

The traditional support of top management for promoting continuous improvement initiatives provided a proper environment for the development of a formal process of on-going improvement (POOGI). The system included all elements needed to record, identify and analyse the primary reasons for delays in task completion. However, once the improvement measures were implemented, no formal time was established to verify their success in addressing delays in the production process. The company considered the verification that the implemented initiatives allowed the organisation to roll reliable offers to be needlessly time-consuming.

Additionally, company B is characterised by continuously monitoring logistics and production-related key performance indicators (KPIs). Formal weekly evaluations determine whether corrective action is necessary based on the KPI results. Measuring KPIs in addition to the buffer consumption provide a broader approach during the establishment of continuous improvement decisions.

Most of the implemented improvement initiatives were focused on the CCR. However, certain additional projects have been developed in non-constrained workstations. Although it did not increase the maximum production capacity, the results show an improved product flow that has contributed to maintaining the decreased lead times.

S-DBR implementation in case C

Element 1: Choking the release in case C

Company C exhibited a large variation in order volume, ranging from hundreds to thousands of medals. Consequently, releasing orders based on a pre-determined buffer time was not easy to implement. The buffer time changed significantly depending on the volume of orders remaining on the shop floor.

The company found a solution by establishing a WIP upper bound. As a result, WIP was limited to half its historical value. This approach is an alternative to that suggested in the S&T tree, which requires releasing orders at a buffer time set to 50% of the original lead time.

The use of the CONWIP principle was supported by the similarities in processing times and the presence of fixed routings along which all orders flow (Spearman et al., 1990) (Hopp & Spearman, 2008).

Finally, the results were similar to the expected findings, with a decreased buffer time. A significant reduction in congestion markedly improved the flow of orders on the shop floor. Figure 4.10 presents how the service level increased from 65% to 80% in less than one year.

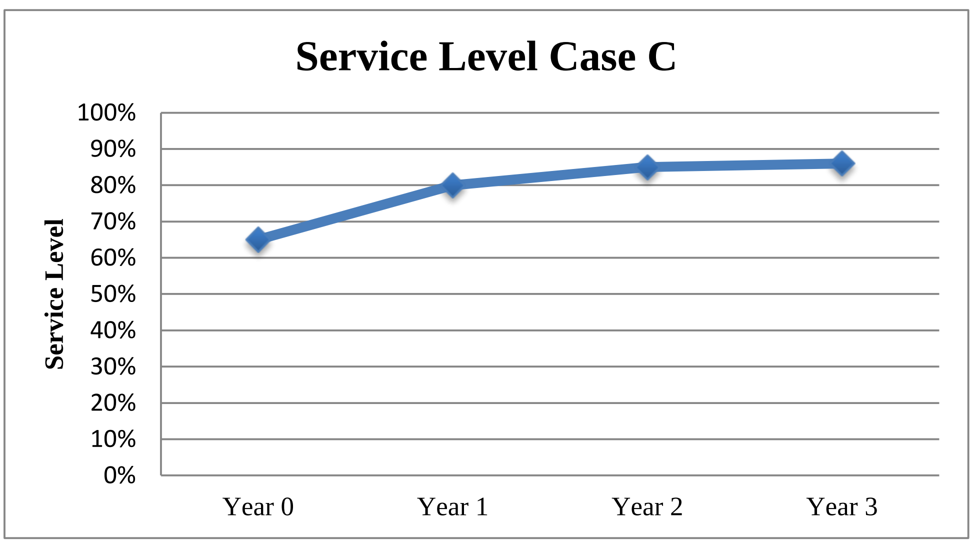


Figure 4.10: Service level at case C

Figure 4.11 presents a company that obtained additional capacity by only reducing congestion on the shop floor, decreasing from 85% of the CCR utilisation to 47% in one year without decreasing production during the first year, which actually increased. During the following two years, the CCR utilisation increased gradually along with increased demands, which is shown in figure 4.12

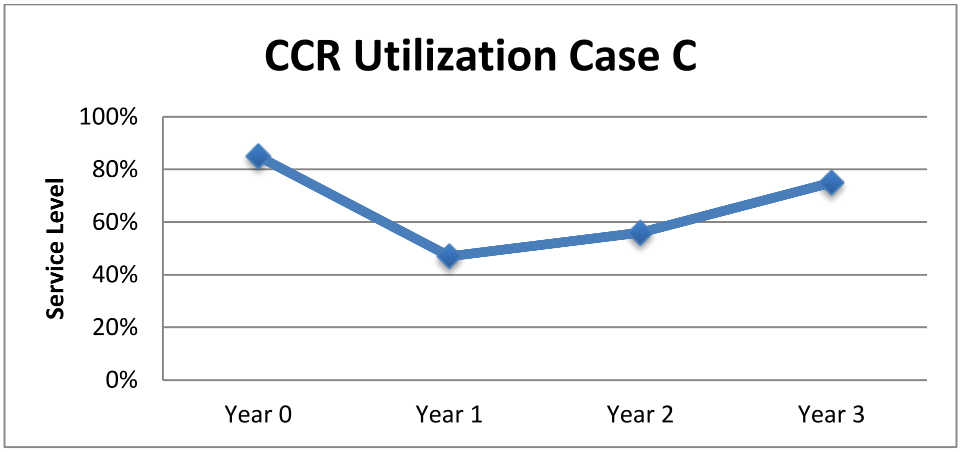


Figure 4.11: CCR utilisation at Case C

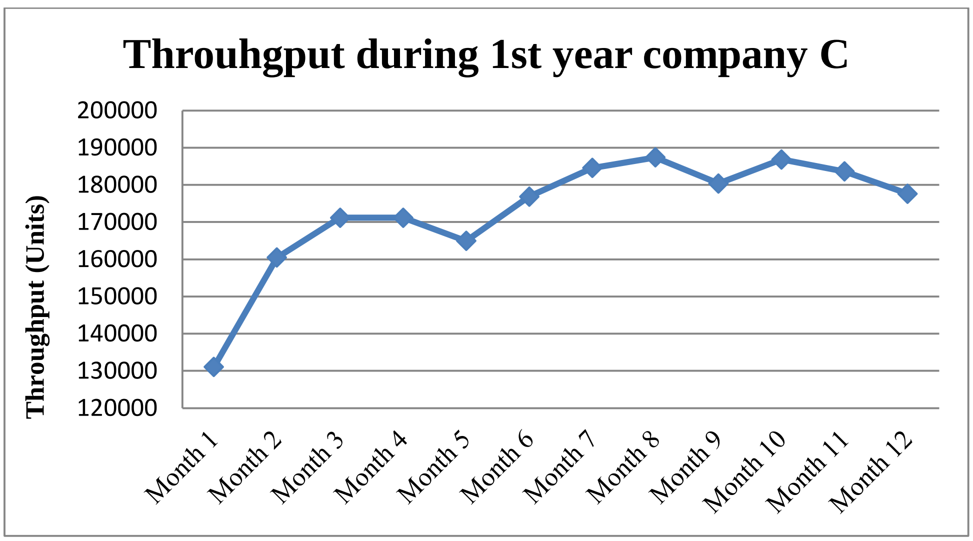


Figure 4.12: Throughput during the first year of implementation Case C

Element 2: Managing the priorities in case C

After orders are released to the floor, the priority is based on the same principles as in the S-DBR methodology. The BM is the only priority system on the floor and is the criterion for developing actions, such as expediting or postponing orders. In addition to software output, the buffer status is presented on one board located at a strategic site in the plant. The foremen are responsible for updating the buffer status; they also review the development of orders on a daily basis according to the three colours defined by the BM system.

Company C has a labour-constrained CCR. As a result, BM plays a crucial role in its management by modifying the number of assigned operators. The number of operators was increased or decreased depending on whether most of an order was in the red or the green zone, respectively. Interestingly, the strict application of the BM principles prevented the labour-constrained CCRs from being a barrier during the S-DBR implementation.

Element 3: Addressing capacity-constrained results in case C

Addressing the CCRs in Company C is not a difficult because the work centres are scheduled with only one 8-hour shift per day. Consequently, during peak demand, it was only necessary to add extra hours to balance the capacity with the demand. Additionally, company C has a work environment with a low resistance to the implementation of changes. This characteristic facilitated the implementation of improvement initiatives originating directly from the shop floor, which are required in some exceptional cases for increasing the capacity.

Element 4: Load control in case C

The PPC in company C is differentiated from traditional S-DBR by its inclusion of a WIP upper bound. In this way, the company tried to reduce congestion on the shop floor by not establishing a predetermined buffer time for choking the release. This change did not significantly affect the load control mechanism with respect to the traditional approach proposed by the S&T tree. In case C, both the due dates and the release times are based on the accumulated planned load of the CCR located at the first stage of the process. Consequently, instead of ½ of the buffer time, one buffer time unit is added to the front of the planned load to determine the first safety due date for all orders.

Maintaining a bounded WIP did not change the load control procedure. This change allows a stationary lead time to be maintained, which significantly increases its due date performance. The results presented in figure 4.13 suggests that the measure was successful because the average lead time decreased from 16 days to 9 days in less than one year (Fig. 12) and the CV decreased from 0.21 to 0.1 during the same period.

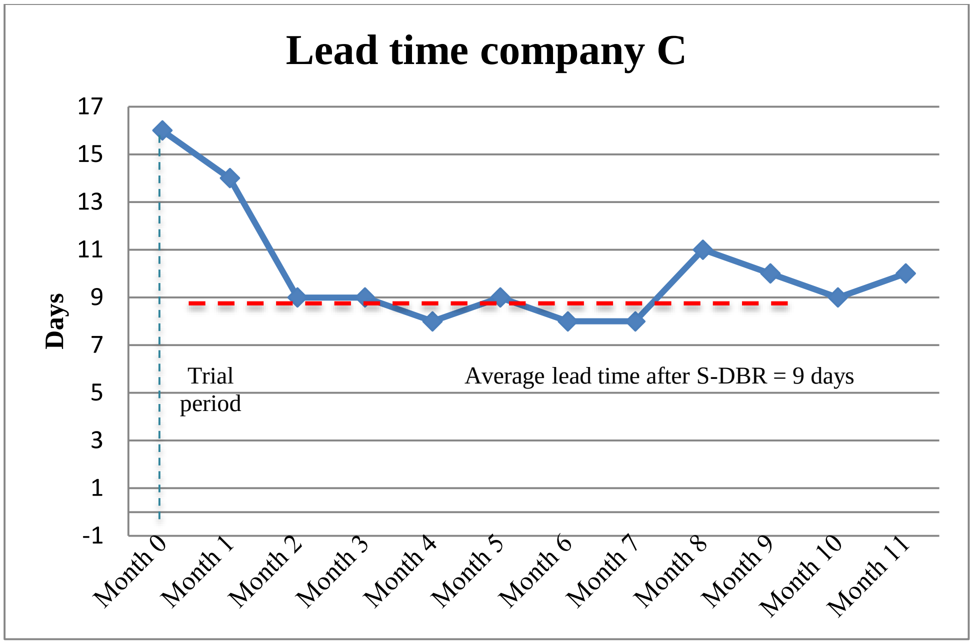


Figure 4. 13: Lead time for company C

In case C, a significant reduction in lead times and their variation in conjunction with a low level of utilisation was not sufficient to achieve the expected DDP of over 99%. The reason for this failure is not directly attributed to the PPCs but to the bad practice of over-promising, which is typically motivated by a common requirement for high volumes of medals a few days before a tournament.

Element 5: Process of on-going improvement (POOGI) in case C

Company C follows the S-DBR methodology for continuous improvement, which proposes collecting information about the causes of disruptions and storing them in a general data bank. With the support of software, the company prioritises the causes according to their frequencies.

In most cases, no formal procedure is established to monitor the implementation progress for the measures. Similarly, after the improvement activities are applied, no formal time period is established to determine their effectiveness. Reliable offers are rolled out without determining whether the company is capable of maintaining it over long periods.

According to the belief that the entire project should be focused directly on the CCR, non-constrained workstations are not considered for the application of continuous improvement initiatives. The consequence is that valuable opportunities that could have significantly improved the flow of orders on the shop floor are wasted.

S-DBR implementation in Case D

Element 1: Choking the release in case D

Company D, which has a high level of utilisation, schedules three 8-hour shifts seven days per week. Considering this scenario, there was no initial optimism at the company with respect to the results of changing the release strategy for orders. The lack of protective capacity suggested that this change would not be sufficient to increase the service level.

However, according to the results presented in figure 4.14 choking the release resulted in outstanding service level results, increasing from 11% to 70% in less than three months. The location of the CCR at the first stage of the process necessitated adding one buffer period to the workload of the CCR when calculating the first safety due date. The results show that despite the high level of utilisation, proper management of congestion can significantly increase the available capacity.

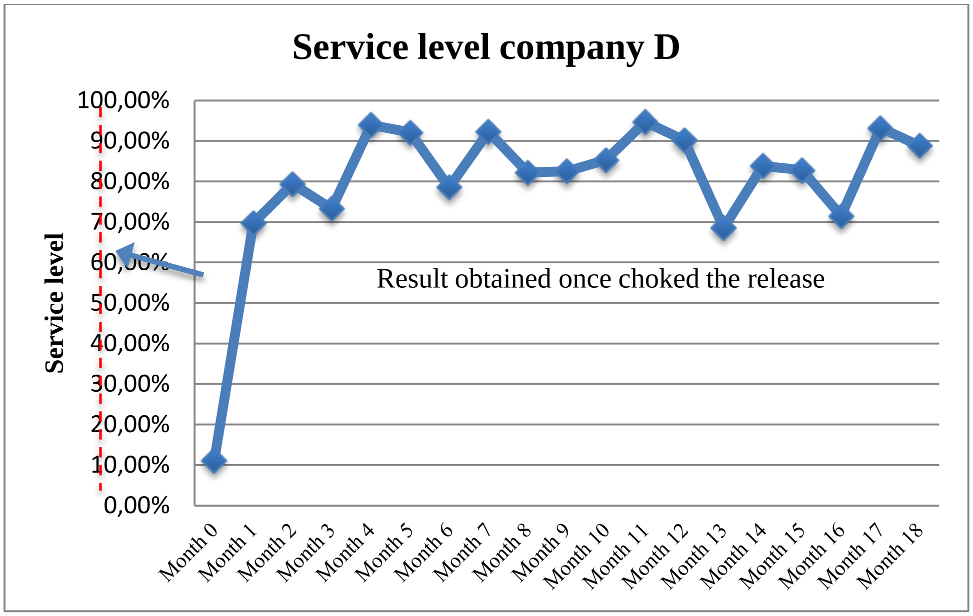


Figure 4.14: Service level for company D

Despite the positive results, a significant percentage of orders are still released later than the scheduled time (Fig. 14), which has not permitted the company to achieve a DDP exceeding 99%. Even considering its decreasing pattern, the non-negligible percentage of orders released past their scheduled due date can be explained by delays during the collection of information from the client before the pressing process. The proposed solution was to consider each order as a project that should be accomplished within a defined time horizon according to the TOC principles for project management.

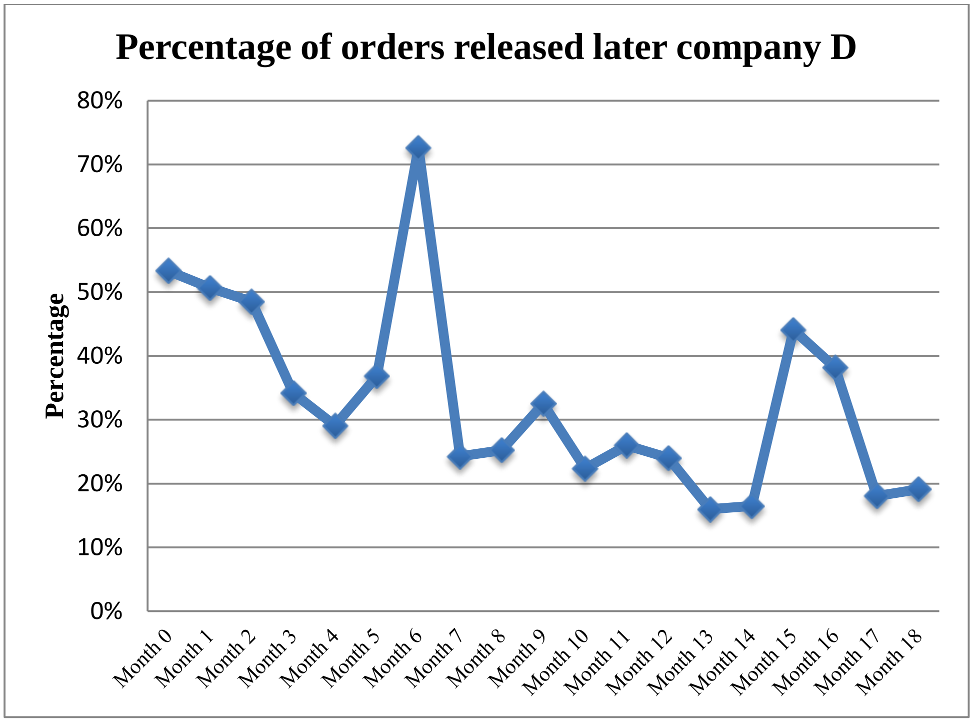


Figure 4.15: Percentage of orders released later at case D

Company D is an offset printing industry characterised by rigid deadlines associated with the publication dates of magazines and catalogues. In this case, it is critical to maintain a strict observance of the priorities on the floor according to the order established by the BM to assure a highly reliable DDP. However, in some cases, the BM priorities are still in conflict with other concerns, such as satisfying the requirements of particular clients. These requirements are typically associated with increased volume demands or delivering products earlier than the original due date, maintaining two priority systems at the same time.

The conflict between priorities typically creates difficulties for operators who lack clear rules as a reference point for taking operational decisions. Additionally, the high level of utilisation increases the difficulty with which company D can achieve a high service level. According to figure 4.16 the historical values are characterised by a wide range of service level variability, ranging from 69% to 94%. This variability is not associated with a significant increase in the volume of production. Instead, this variability may be related to poor management of priorities on the shop floor.

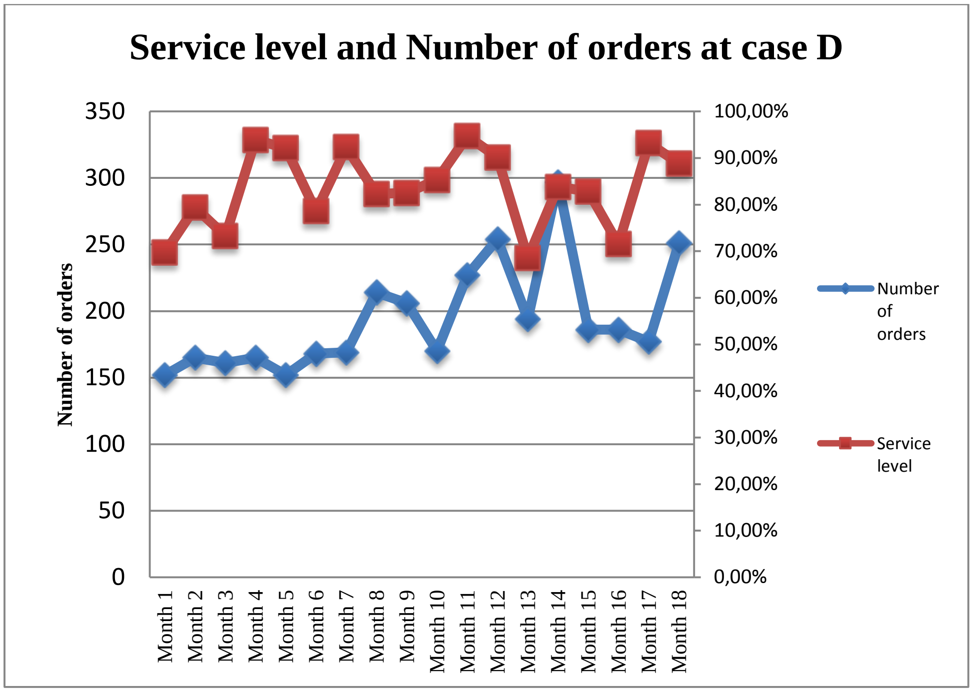


Figure 4.16: Number of orders and service level for case D

Element 3: Addressing capacity-constrained results in case D

Company D is characterised by its reactive approach, taking improvement initiatives only after the causes of disruptions have seriously affected company performance. There is no formal procedure for addressing the issues affecting an order's buffer consumption during the week. The application of a reactive approach has seriously limited the company's capacity to achieve a consistent system with respect to the operational indicators. For example, several indicators, such as the service level and the tardiness, improved significantly immediately after implementing S-DBR. However, according to figure 4.17 the improvement of both values plateaued, with instability remaining after implementation.

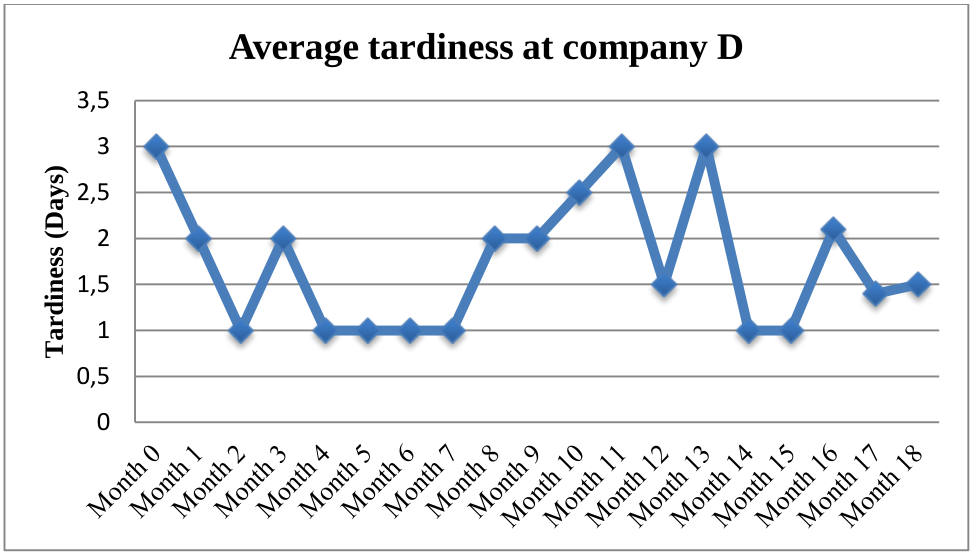


Figure 4.17: Average tardiness at case D

A substantially lack of relevance has led this company to exploit its CCRs. This should be a critical aspect in an environment such as that of company D, where the primary restriction is internal. This is a result of the company's initial success, where the initial change was perceived as a less congested shop floor, which generated conformity at the plant.

Element 4: Load control in case D

In case D, there is a strong difference in the processing times at the CCR within each product family. This difference significantly influenced the accuracy of the established workload on the CCR during the first weeks of implementation. Therefore, the establishment of sub-family divisions was necessary, significantly improving the accuracy of the workload estimations. However, the S&T tree does not propose any formal measure for avoiding the negative effects of an inaccurate estimation.

Additionally, the process had setup times that could be significantly affected by the job sequence. Consequently, it was necessary to establish suggested sequencings aimed to minimise preparation times. In all of the cases, any change in sequencing was subordinated to the BM rules by the priority system on the floor.

Element 5: Process of on-going improvement (POOGI) in case D

Company D possesses a poor system for connecting non-trivial disruptions to technical or operational problems. Any initiative has a reactive characteristic, being applied only when a serious effect on the operational performance is noted. Due to the lack of a real POOGI system, the inertia is sometimes served as a system constraint and creates a standstill in the operational performance and results in limited flexibility for responding to demand changes. In any case, a formal procedure for monitoring the implementation and verifying the effectiveness of the implemented measures has been employed.

4.2.8 Cross-case Analysis

The cross-case analysis in this section focuses on identifying the commonalities and differences across the four case companies (McCutcheon & Meredith, 1993) during the S-DBR implementation. This comparison is achieved by comparing decisions through each of the five steps proposed by the S-DBR S&T tree and their results according to the different characteristics of the companies. Supported by the literature or conceptual reasoning, possible correlations between the operational performance and the decisions made during the S-DBR implementation are identified. The following table shows the commonalities and differences found during the S-DBR implementation for the four companies selected in the study. The table is organised according to the strategies proposed for each of the five points that comprise the S-DBR S&T tree (E. Goldratt, 2006).

Table 4.4 Cross-case analysis of S-DBR implementation in four sample companies.

S-DBR implementation elements		Company A	Company B	Company C	Company D
Element 1: Choking the release					
1.1	Setting the production buffer (PB) to 50% of the original lead time	***Fully implemented***	***Fully implemented***	***Not implemented:*** Historical WIP is reduced to 50%	***Partially implemented:*** The PB is equivalent to 30% of the original lead time
1.2	PBs are created when the difference between them exceeds 25%	***Fully implemented:*** One buffer time per family	***Not implemented:*** No difference between PBs	***Not implemented:*** No difference between PBs	***Fully implemented:*** One buffer time per family
1.3	The release schedule is effectively followed	***Partially implemented:*** 5% of orders are released out of schedule	***Fully implemented:*** Fewer than 1% of orders are released out of schedule	***Partially implemented:*** 5% of orders are released out of schedule	***Partially implemented:*** 20% of orders are released out of schedule
Element 2: Managing the priorities					
2.1	The system provides an updated list of buffer status consumption	***Fully implemented:*** Software provides buffer status information	***Fully implemented:*** Software provides buffer status information	***Fully implemented:*** Software provides buffer status information	***Fully implemented:*** Software provides buffer status information
2.2	Order buffer status is shared among departments	***Fully implemented:*** Reports are integrated among departments	***Fully implemented:*** Reports are integrated among departments	***Fully implemented:*** Reports are integrated among departments	***Fully implemented:*** Reports are integrated among departments
2.3	The company offers visual controls to show buffer status	***Fully implemented:*** LCD screens and coloured tags adhered to WIP	***Fully implemented:*** LCD screens	***Fully implemented:*** Buffer consumption information on boards	***Fully implemented:*** LCD screens
2.4	The foremen enforce BM as the only priority system	***Partially implemented:*** Additional sequencing rules are subordinated to the BM priorities	***Fully implemented***	***Fully implemented***	***Partially implemented:*** Additional sequencing rules are subordinated to the BM priorities
2.5	Management does not participate in violating the BM priorities	***Partially implemented:*** Management intervenes occasionally	***Fully implemented:*** No intervention	***Fully implemented:*** No intervention	***Partially implemented:*** Management intervenes occasionally

	S-DBR implementation elements	Company A	Company B	Company C	Company D
	Element 3: Dealing with the capacity constrained resources				
3.1	There is a formal procedure for detecting emerging CCRs	***Not implemented:*** A reactive approach identifies emerging CCRs based on order's buffer consumption	***Full implemented:*** Formal procedure monitors workload resources weekly	***Not implemented:*** There is no formal procedure implemented	***Not implemented:*** A reactive approach identifies emerging CCRs based on order's buffer consumption
3.2	Establishment of a trial period previous roll out the reliability offer	***Not implemented***	***Not implemented***	***Not implemented***	***Not implemented***
	Element 4: Load control				
4.1	DDs are determined according to the first slot in the CCR, adding ½ of the PB	***Not implemented:*** 1 PB is added because the CCR is located on the front end of the routing	***Fully implemented:*** The CCR is located in the middle of the routing	***Not implemented:*** 1 PB is added because the CCR is located on the front end of the routing	***Fully implemented:*** The CCR is located in the middle of the routing
4.2	The organisation provides the DD in less than 1 min.	***Fully implemented***	***Fully implemented***	***Fully implemented***	***Fully implemented***
4.3	The company does not make commitments to less than the standard delivery lead time (DLT)	***Fully implemented:*** Orders with a shorter DLT are subjected to extra charges	***Fully implemented***	***Fully implemented:*** Orders with a shorter DLT are subjected to extra charges	***Partially implemented:*** Top management intervenes to offer orders shorter than the DLT
4.4	Sales forces are subordinated to operations when making a commitment to the client	***Fully implemented***	***Fully implemented***	***Fully implemented***	***Partially implemented:*** The sales force is not subordinated to operations
	Element 5: POGGI				
5.1	Causes of non-trivial disruption are stored	**Fully implemented**	**Fully implemented**	**Fully implemented**	**Fully implemented**
5.2	There is a formal procedure for analysing causes of disruptions	**Not implemented**	**Fully implemented**	**Partially implemented:** Weekly meetings are held to analyse the causes of disruptions; no monitoring	**Not implemented**
5.3	Orders with buffer consumption in red are separately analysed	**Not implemented**	**Not implemented**	**Not implemented**	**Not implemented**

Element 1: Choking the release

By setting the production buffer to a fraction of the original lead time, which is element 1.1 of the S-DBR implementation, can be considered the step with the strongest impact on a company's performance. Outstanding results with respect to the service levels were presented in figure 4.18 for all of the cases. The results were similar among the cases, even in case C, where the WIP and not the buffer time was reduced by half, or case D, where the tightness of the due dates only allowed the buffer time to be reduced by 33%.

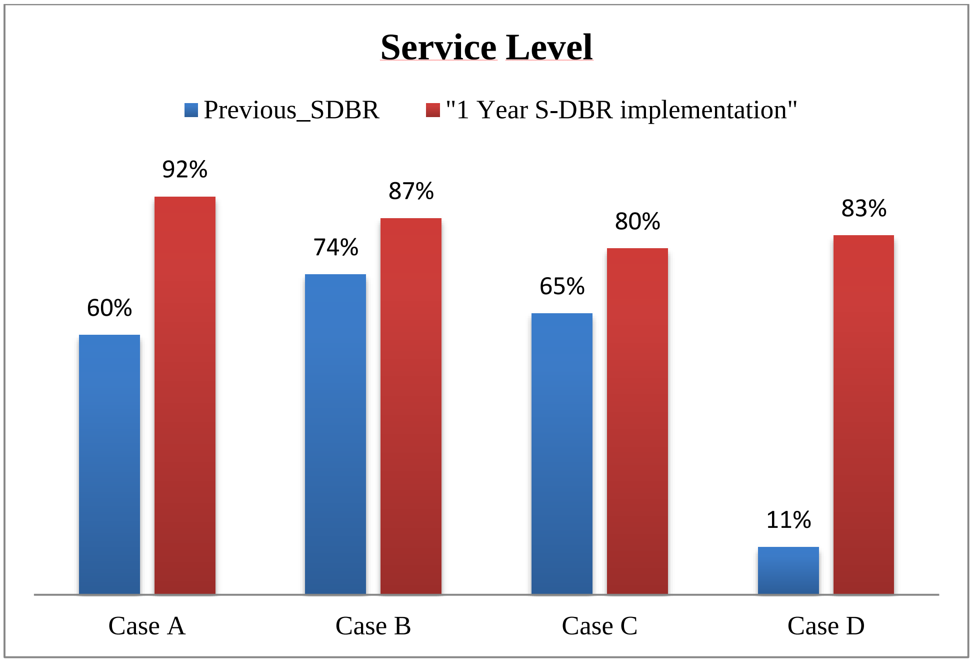


Figure 4.18: Service level before and one year after S-DBR implementation

The service level improvement for case C did not include the suggested halving of the lead time; instead, the CONWIP concept of restricting the WIP level on the line was applied. The results support the suggestion put forth by previous authors, such as Lee et al. (2009), that the lack of a method for controlling the release of orders is a primary cause of prolonged lead times and DD disruptions. Similarly, the results for case C validate the effectiveness of other initiatives that propose PPCs with a clear focus on controlling the releasing of orders as the primary means for achieving stable lead times on the shop floor. For example, several initiatives, such as CONWIP (Luh, Zhou, & Tomastik, 2000), WLC (Henrich, 2005) and POLCA (Fernandes & do Carmo-Silva, 2006) exhibit DDP results that are similar to those obtained using S-DBR. In all of these initiatives, the release of orders is subjected to the situation on the shop floor. However, S-

DBR offers considerably more simplicity than other systems that do not suggest more than reducing the current lead time to half and basing the release of orders on the buffer time (E. Goldratt, 2006). This aspect likely explains why this step is easy to implement; the case study companies did not report any difficulty during its implementation.

Once the aforementioned step was applied, the methodology suggests that a company should evaluating the differences between the production buffers (PBs) for each family. In the case of differences exceeding 25%, separate PBs are suggested. This separation was applied in cases A and D, where one PB was necessary for different sub-families. Having separate PBs is a good practice even in other methodologies, such as the lean methodology for high-mix and low-volume environments (Lane & Shook, 2007).

Maintaining a strict observance of the release schedule is still considered critical for obtaining a floor populated only with orders that must be filled within a predetermined horizon. Based on the step proposed by the S&T tree, the release schedule depends primarily on maintaining a group of disciplined and appropriately trained operators. The lack of discipline is likely the primary cause of not fully accomplishing this goal within the first two cases. In case A, orders are released to minimise the effect of sequencing with respect to preparation times. In case C, extra time is used for overpromised orders. However, in case D, 20% of orders released late could be directly related to delays before the design process, which exceeds the effect caused by a lack of discipline.

The impact of releasing orders that violate the proposed schedule can be observed in figure 4.19 by comparing the DDPs of companies B and D. In both cases, the utilisation is near 100% at their CCRs. However, the DDP of company B is significantly better than that of company D. The comparison is possible because both plants maintain similar CCR utilisations, with the primary difference being that company B releases orders according to the S-DBR proposed schedule.

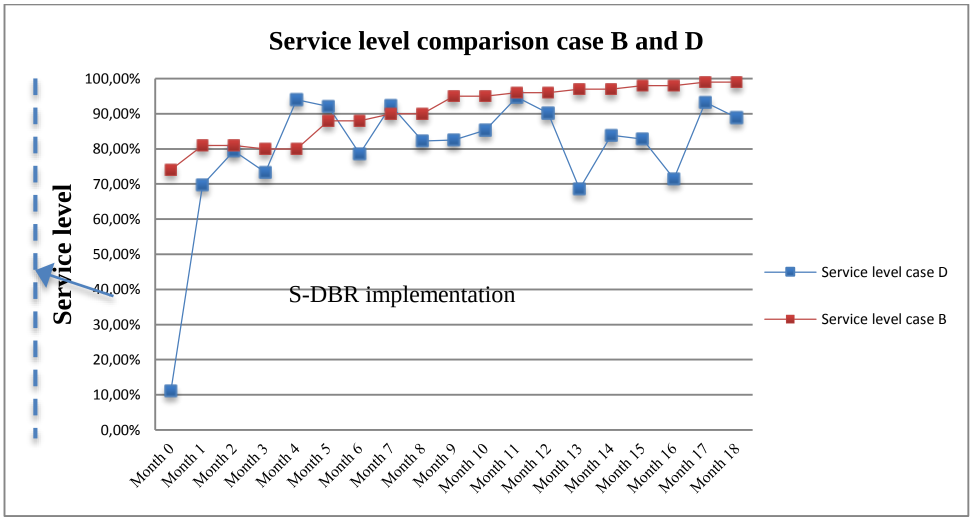


Figure 4. 19: DDP comparison for companies B and D

Element 2: Managing the Priorities

In all four cases, the companies provide operators and the remaining departments with the necessary information regarding the buffer status of all orders. Additionally, visual controls were easily implemented to bring the operators closer to the necessary BM information that is used to support decisions during execution. The system of colours is highly intuitive and can be easily reproduced in numerous ways: applying tags directly to WIP and using LCD screens at company A, creating a central board summarising the buffer consumption information for orders at company C, and, similar to case A, implementing screens that display the real buffer status of orders in cases B and D.

Although all of the companies maintained the necessary systems for collecting and presenting the BM information, this was not maintained as the only priority system on the floor in all cases. In companies A and D, such situations as the relationship between the sequencing of products and the time spent on preparation activities generated a conflict between increasing local performance and achieving a high DDP.

Additionally, cases A and D are similar with respect to the level of intervention of top management in decisions related to the release of orders. In most instances, the changes proposed by the management violate the predetermined path established by the BM rules. In both cases A and D, the reasons are related to incorporating an alternative priority system based on the importance of a certain client. This situation is especially critical considering the high level of CCR utilisation. A high level of utilisation minimises the order slack time, making a system sensitive to even small changes.

Element 3: Addressing capacity-constrained results

S-DBR does not require detailed scheduling for the CCR. Based on the S-DBR methodology, the sequence of the CCR is not planned (Schragenheim et al., 2006b); instead, the sequence is simply a mechanism applied to prevent offering due dates that are not in accordance with the actual load of the CCR. However, overly optimistic due dates can be generated by not accurately identifying where the internal restriction is located.

Despite the critical nature of this step, the collected empirical evidence indicates that only one of the four cases has implemented a formal procedure for evaluating the emergence of a new CCR. In the other cases, a reactive approach focuses on the CCRs only when a new internal constraint has severely affected a company’s DDP.

This limited attention to monitoring the workload of resources is related to day-to-day management at these companies, which is primary focused on the actual CCR. Significant consequences were primarily identified in case A, where the market conditions generated a change in the product mix and a subsequent CCR re-allocation.

It is notorious in figure 4.20 that the increasing utilization of the printers in case A not was not buffered with any measure that prevented a significant effect on operational performance. Additionally, the lead times of the products associated with the printers was another signal that could have alerted the company of a future negative effect. However no counter-measures aimed at providing additional capacity at the emerging CCR were applied. The company considered taking measures to increase printer capacity only when they observed a significant service level reduction during Year 6.

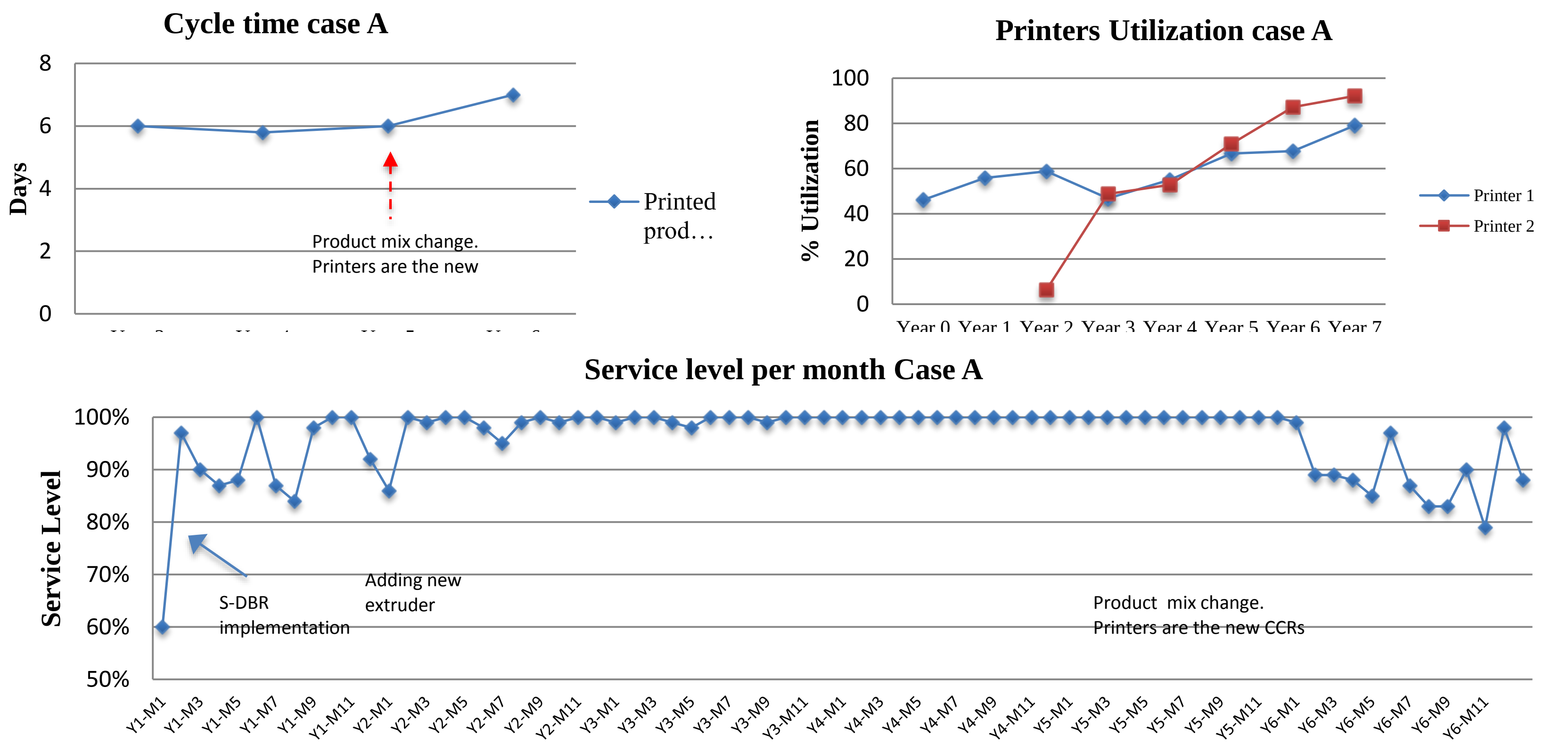


Figure 4.20 Lead time, service level and utilisation for company A

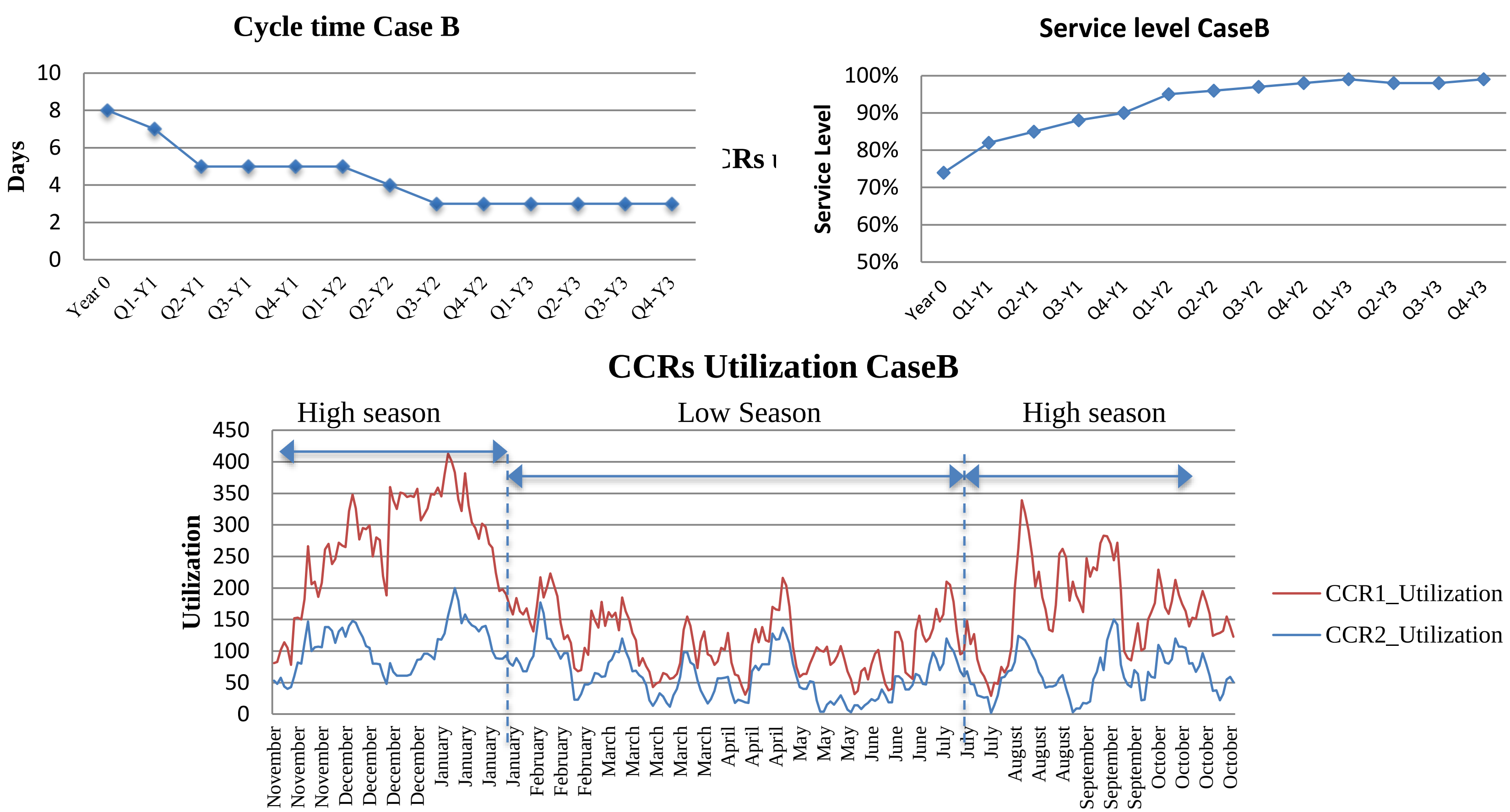


Figure 4.21: Lead time, service level and utilisation for company B

Comparing the operational performance of companies A and B suggests that appropriate capacity monitoring and management can result in good performance, even in situations with a high variability in the CCR workload. Company B has a high level of utilisation that exhibits a remarkable seasonality in demand. Depending on the season, the CCR utilisation changes significantly. However, this market characteristic has not resulted in sudden changes resulting in negative effects on cycle times and consequently DDP. In fact, the cycle times have decreased (Fig. 20), and the service level has increased (Fig. 20). Therefore, the difference between companies A and B cannot be attributed to the level of utilisation or the stationarity of the demand. The primary difference between the two companies is more strongly related to the inappropriate management of the provided information regarding CCR workloads.

Finally, the differences between companies A and B are due to the differences between elevating or exploring the capacity of the CCRs. In this way, company A is more focused on significantly increasing the capacity of internal restrictions by acquiring additional equipment. Meanwhile, company B is continuously searching for continuous improvement alternatives that allow small capacity increases, even during peak demand periods.

Although company B has a formal procedure for evaluating the emergence of a new CCR that is similar to the other companies, no formal trial period to determine when the DDP exceeded 99% was applied during the implementation. The S&T tree proposes a trial time equal to the production buffer before giving the sales force the green light to make reliable offers. In some cases, this time is likely not sufficient to determine whether a company is able to offer reliable DDP. Consequently, many companies consider this step meaningless, which may be an opportunity for the application of alternative methods aimed to enhance S-DBR performance.

Element 4: Load Control

Originally assumed to be at the middle of the routing, the S-DBR S&T tree proposes adding ½ of the production buffer to the first available slot in the CCR to establish due date commitments. However, in cases A and C the CCR is located at the front end of the routings, making the application of this rule inappropriate. In both cases, applying the original rule would generate overly optimistic due dates. As a result, it was implied that an order would go through nearly the entire routing in just half of the production buffer, while the first ½ of the production buffer was wasted on routing that did not exist.

In case C, since the beginning of the implementation, it was possible to consider the real location of the CCR when establishing due dates and the release time of orders. Similarly, in case A, it was possible to apply an alternative method that considers the location of the CCR. However, it was possible to collect historical information in case A that corresponds to the first weeks of the S-DBR implementation. The figure 4.22 presents the low initial DDP resulting from combining poor processing time estimates and considering the incorrect assumption regarding the location of the CCR.

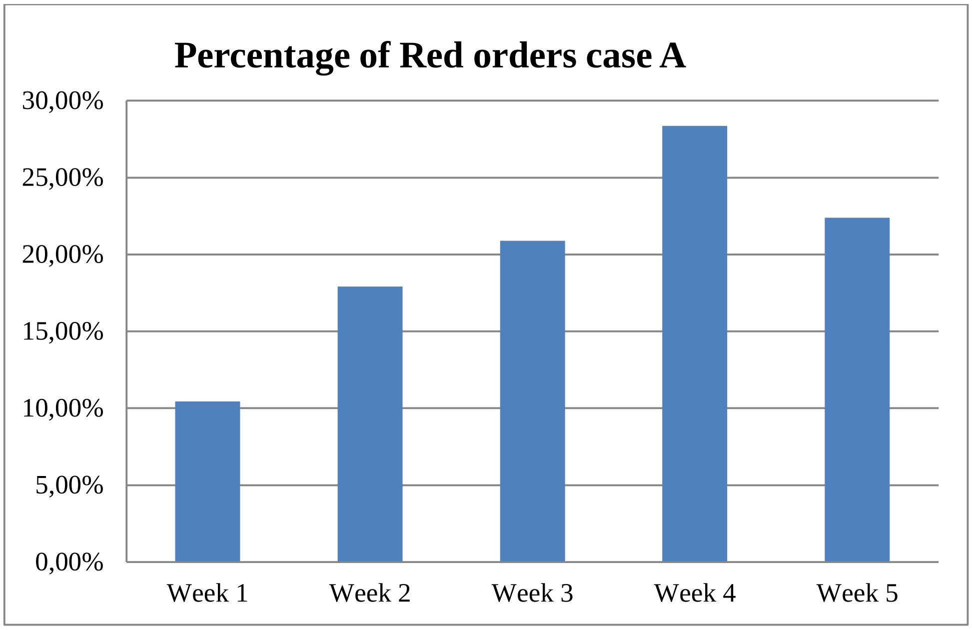


Figure 4.22: Percentage of orders that penetrate red zone

Finally, the solution applied in both cases was similar to that proposed by Lee et al. (2010), which considers the order due date and the order release date to be

Order due date = first available slot time on CCR + (1-α)*PB,

Order release date = first available slot time on CCR minus α∗PB,

where the value of the correction factor α should be less than 0.5 and

PB = Production Buffer.

At companies A and C, the correction factor was 0, in accordance with the location of the CCR at the first station of the process.

Case C applied the same mechanism as case A to calculate due dates, which is particularly interesting because case C maintained an upper WIP boundary. This difference did not affect the load control mechanism; although it did reduce lead time variability. The buffer time used to calculate the FSDD in company C was expected to be much more predictable than that in situations where WIP may achieve extremely high or low values (Hopp & Spearman, 1993). The principle of applying the WLC methodology to monitor the release of orders maintains control over WIP queues and results in predictable lead times (M. Land, 2006).

Differences in the operational performance between this alternative method and the original could not identified. Any difference in performance is directly attributed to improperly applying the elements proposed by the S&T tree.

In addition to considering the real location of the internal constraint, another critical factor for achieving highly reliable due dates is maintaining appropriate processing time estimates. However, the S&T tree does not propose any procedure to determine the accuracy of processing time estimates in the CCR. The S&T tree uniquely suggests determining the differences between the production buffers related to each of the different product families. In fact, in most cases, the processing time estimates in the CCR are considered the same for all products within the same family.

This issue was observed in cases A and D, where the high product variability within each family significantly affected the workload estimates. Applying a unique average CCR processing time for all of the products significantly affected the accuracy of the workload estimates. In both cases, the workload appeared to be underestimated; consequently, the due dates were offered earlier than the companies were able to manage. This issue was solved by separating the products with the greatest mean processing time difference from the family. Because this issue appeared during the first weeks of implementation, it did not significantly affect the long-term operational performance measures.

S-DBR is based on the Goldratt philosophy, which proposes that a system need not be more accurate than the noise. However, the previous finding suggests that companies should be cautious when implementing S-DBR, i.e., not minimising the planning before determining the reality of the process. For example, including an additional step aimed to validate the processing time estimates may be an opportunity to enhance the system performance of S-DBR.

Finally, maintaining an appropriate system for providing due dates is not sufficient if a company violates the rules. Committing to less than the standard delivery lead time or not subordinating the sales force to the reality of the production process can significantly jeopardise the effectiveness of the S-DBR implementation. This is precisely the case of company D, where top management encouraged the sales forces to suggest due dates according to the requirements of the company's most important clients. This type of measure simply promoted temporal and local optimisations based on the benefits of one department, comprising the goal of improving system-wide performance. This aspect is an additional factor that has contributed to the long-term system inconsistency with respect to DDP.

Finally, the sequence of jobs in the planned load is determined by the market. Consequently, it is assumed that this sequence does not significantly influence the CCR capacity (Schragenheim et al., 2009c). This assumption is not completely accurate in cases A and D, where the nature of the process causes certain sequences to affect the CCR capacity. In these cases, additional considerations for sequencing orders were implemented, such as a group of rules that suggests the best combination of orders to minimise preparation times. The workers were trained to make use of these special considerations that were subordinated to the market and expressed through the BM priorities.

Element 5: Process of on-going improvement (POOGI)

Maintaining a system of continuous improvements has probably been the most deficient element in most of the companies analysed in this study. Although the causes of disruptions are reported and stored, only one company has established a true formal procedure for the analysis and proposal of solutions to reduce these disruptions. The data demonstrate that the consequence of this deficiency depends principally on the level of protective capacity maintained by an individual company.

For example, case A suffered the consequences of not maintaining a continuous improvement system only when the location of the CCR changed, which significantly affected DDP. Similarly, case D has maintained a DDP deficiency, not achieving its goal of exceeding 99%.

However, company C was not affected by its lack of a formal continuous improvement system. Scheduling the plant in just one 8-hour shift per day provides company C with the necessary protective capacity to buffer any internal or external change. In this respect, the deficiencies identified in case C are more important when overpromising occurs.

Finally, case B is a good example of how maintaining a formal continuous improvement plan can effectively improve the total performance of a plant, even when maintaining a high level of utilisation. Typically, the applied tools are among the seven basic tools of quality. However, company B has applied more elaborate methodologies, such as total productive maintenance (TPM). The application of this methodology has resulted in an increased service level, even during demand peaks. The focus on preventing any type of slack before it occurs has increased the availability of the CCR, even during periods of high demand.

The results suggest that maintaining a program of continuous improvement is critical for responding to internal or external changes that may significantly harm lead times. Not implementing a system to identify opportunities for continuous improvement makes a process highly sensitive to changes. In this case, S-DBR is capable of maintaining good internal and external environments without the necessary robustness of managing changes presented in reality.

The cross-case analysis presented above has provided an understanding of how the different characteristics of the studied companies and the decisions that they have made during the application of the methodology have influenced their operational performance. However, in some cases, the constraint to achieve a better performance is part of the S-DBR methodology itself. The empirical results have demonstrated some limitations that suggest the application of alternative methods for enhancing the S-DBR methodology.

5

Alternative methods for enhancing S-DBR performance

This chapter explores each opportunity to improve S-DBR according to the five elements proposed by the S&T tree in accordance with the empirical results obtained from the case study presented in the preceding chapter.

5.1 S-DBR Opportunities of improvement

According to several authors, no PPC is universally appropriate (Tatsiopoulos & Mekras, 1999) (B. L. MacCarthy & Fernandes, 2000) (Stevenson* et al., 2005). Many factors can motivate whether a specific PPC is adopted. Consequently, this study does not intend to propose a solution as a perfect approach with the expectation of satisfying all of the particular requirements of Ecuadorian SMEs. In this way, according to previous experiences, S-DBR appears to be a suitable approach for the process and market characteristics of Ecuadorian SMEs, although the method still has limitations that may prevent its successful implementation.

Based on the experiences implementing S-DBR in the previous cases, it was possible to identify potential opportunities for improvement. The following table presents these opportunities according to the implementation steps established by Goldratt (2006). In this study, we propose the introduction of methods previously developed for other methodologies and present the means of their implementation in combination with the S-DBR concepts.

Table 5.1: S-DBR potential opportunities of improvement and impacts

Implementation Step	S-DBR Drawbacks	Impacts
Managing the CCRs	Considering the trial time as a period equal to the production buffer time may not be sufficient to roll out reliable offers.	Releasing a reliable offer without the necessary confidence can significantly jeopardise the capacity of the plant to achieve a high level of DDP.
Load control	S-DBR assumes that the CCR is located at the middle of the routing.	If the CCR is located at the front end of the routing, the company may overpromise, offering overly optimistic due dates. If the CCR is located at the back end of the routing, the orders may be released too late, causing idleness at the CCR.
	There is no formal mechanism for evaluating the accuracy of the estimated processing times at the CCR.	Underestimating the CCR's workload can lead to promising a due date earlier than the plant is capable of delivering. Overestimating the workload can cause the work to finish earlier than planned, causing the CCR to be idle and potentially losing sales.
POOGI-systematically improving flow	Focusing the improvement projects exclusively on capacity-constrained resources.	In some opportunities, it is not feasible to directly exploit the CCR due to physical or economical limitations. However, focusing exclusively on the CCRs causes other good opportunities at non-bottleneck stations to be lost, losing the opportunity to achieve better global performance.

5.1.1 Managing the CCR. Using a P control chart for service level monitoring

The empirical evidence presented in chapter 4 suggests a lack of clarity among practitioners with respect to the length of the trial period required before rolling out reliable offers. The trial period is the time during which the company should evaluate its due date performance. According to the S&T tree, the company is only qualified to roll out a reliable offer if its DDP exceeds 99% during a period equal to the production buffer time. Despite this suggestion, none of the studied companies implemented this step.

In this respect, we propose the application of a tool such as the P chart, which is considered to be a good option for determining whether there is a significant change resulting from improvement initiatives in a particular process (Breyfogle III, 2003). In this case, the p chart is directly applied to indicate when there is significant evidence that a company has achieved a highly reliable DDP.

The p chart application is supported by the service level description, which is described as the proportion of orders whose cycle is equal to or less than the established lead time (Hopp & Spearman, 2008). Consequently, as a mathematical expression, the service level can be written as $P=\frac{x}{n}$, where n is the total number of orders committed within a planning horizon, while x represents the total number of orders for which the lead time is equal to or less than the proposed lead time. The term *n* is associated with subgroups of varying size, and x is a characteristic described as “yes” or “no” depending on whether an order is fulfilled within the proposed lead times. In this way, the p chart can be applied in environments in which the total number of orders released during a planning horizon is either fixed or variable.

The p chart is based on a 3-sigma deviation from the process mean, where the 3-sigma control limits are associated with a normal approximation of a binomial distribution. Thus, x should be described as a random variable that is binomially distributed (Montgomery, 2007). This assumptions is precisely the basis for the control limit calculations:

LCL = $\bar{p} + 3\sqrt{\frac{\bar{p}\,(1-\bar{p}\,)}{N}}$,

LC = $\bar{p}$,

LIC = $\bar{p} - 3\sqrt{\frac{\bar{p}\,(1-\bar{p}\,)}{N}}$,

where $\bar{p}$ is the total number of non-conforming orders divided by the total number of orders N. According to the previous equations, the control limits can vary according to the number of orders included in each sub-group.

Although the p chart is a useful tool for monitoring service level performance, it has drawbacks that should be considered during its application. One such drawback is the normal approximation necessary for the establishment of the p chart control limits. This assumption has exceptions when the product of n and p does not exceed 5. Therefore, for a very low proportion of non-conforming orders (p<<0,05), the size of the sample should be increased significantly.

Additionally, the p chart has an important disadvantage in requiring the detection of small changes. There is a non-linear relationship between the change that must be detected (δ) and the size of the sample. For example, detecting a change of 5% with a 50% chance requires at least a sample size of 576 orders considering $\bar{p} = 0.2$:

n ≥ $\left(\frac{3}{\delta}\right)^2 \bar{p}\,(1-\bar{p}\,)$,

n ≥ $\left(\frac{3}{0{,}05}\right)^2 0{,}2\,(1-0{,}2\,)$, n ≥576.

Using fewer samples will significantly affect the normal approximation, dramatically increasing the false alarm probability from the 0.0135 calculated for an $\overline{\mathrm{X}}$ chart. Consequently, the p chart is a tool for determining large shifts. For example, considering the same process as above with $\bar{\mathrm{p}} = 0{,}2$, a sample sizes of only approximately 40 orders is necessary to detect with a 50% chance whether a process has changed from 80% to 99%:

$$n \geq \left(\frac{3}{\delta}\right)^2 \bar{p}\,(1-\bar{p}\,),$$

$$n \geq \left(\frac{3}{0{,}19}\right)^2 0{,}2\,(1-0{,}2\,),$$

n ≥40.

Based on this information, a p-chart is an appropriate instrument to monitor the effectiveness of the S-DBR methodology, especially during the initial stages of its implementation. According to the experiences implementing S-DBR of the studied companies, it is possible recognise the dramatic changes in service level performance (Fig. 22). Similarly, to determine whether a company is ready to roll out reliable offers, increasing its service level performance to at least a 99% is necessary. In most cases, this represents a quantum leap between the current and expected service level performances.

Consequently, in addition to the initial periods of implementation, the p control chart can be applied to determine whether the measures for exposing or increasing additional capacity were effective. Therefore, the suggested test is that which is traditionally applied to p control charts to determine the presence of a special cause of variation. This test is based on identifying a pattern in which at least nine points are in a row in zone C or beyond on the same side of the central line. For a significant change, the control limits should be recalculated. The figure 5.1 could be considered an evidence to state that the measures applied on the CCRs have been effective. The figure 5.1 can be used as evidence that the measures applied to the CCRs have been effective

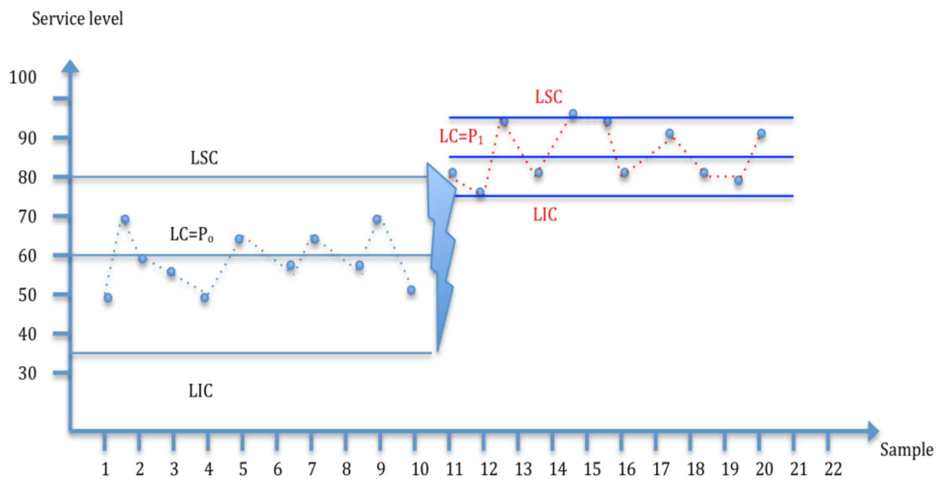


Figure 5.1: P-chart for monitoring initiatives for exposing CCR's capacity

Finally, applying a control chart instead of establishing a trial period will diminish the subjectivity regarding the decision of whether to release reliable offers to the market. A control chart provides practitioners with support for deciding whether an increase effectively represents a change at the service level or is just an effect of a special cause of variation. In this way, the p chart is a proper complement in the evaluation of initiatives aimed to exploit or increase capacity of the critical resources.

5.1.2 Load Control. Procedure aimed to support CCRs not located in the middle of the routing

The location of the CCRs in the middle of the routing is the primary assumption of the load control mechanism established by the S-DBR methodology. This principle, proposed by the S-DBR S&T tree, is aimed at obtaining a due date commitment based on the actual CCR load. However, the practice includes companies such as cases A and C, where the CCR is not located at the middle of the routing. For such companies, maintaining the original assumption may hinder the S-DBR implementation. This consequence depends on the real location of the CCR. In both cases, the CCR was located at the beginning of the routing; thus, adding ½ of the buffer to the first available slot in the CCR which is presented in figure 5.2 can result in overly optimistic due dates.

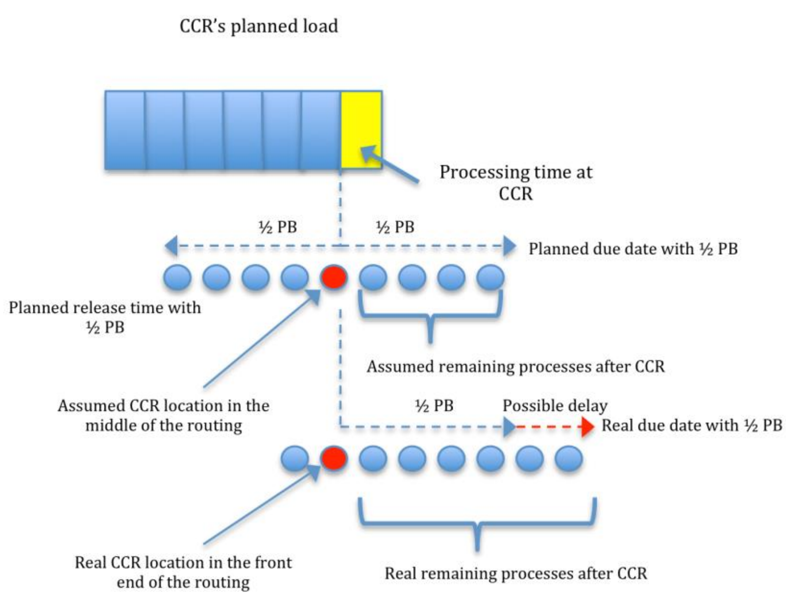


Figure 5.2: Determining due dates with the CCR located at the front end of routing

However, a CCR located at the back end of the routing can have the opposite effect. In this case, maintaining the traditional load control approach will release orders too late, generating an idle CCR. Despite not affecting a company's DDP, an excessively low planned load can result in the loss of valuable sales .

Considering these circumstances, Lee (2010) proposed the inclusion of corrective factors depending on the real location of the CCR. These factors are aimed to provide better approximations of due dates and release dates for orders.

If the CCR is located at the front end of the routing,

Order due date = First available slot time on CCR plus (1-α)*production buffer,

Order release date = First available slot time on CCR minus α*production buffer.

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

Order due date = First available slot time on CCR plus (1-β)*production buffer

Order release date = First available slot time on CCR minus β*production buffer.

5.1.3 Choking the release. Mechanism to evaluate the accuracy of the processing time estimates at the CCR

According to the S-DBR definition, buffer times are liberal estimates of the elapsed time from the release of products to the shipping dock (Schragenheim et al., 2009b). These time buffers are typically established for a group of products considering the similarity of their production routing and processing times. Importantly, products included within the same buffer time do not necessarily maintain the same processing time at the CCR. However, the collected empirical evidence has shown that this assumption is a common practice.

The consequences of this approach can be observed in cases A and D, where maintaining an average processing time for products within the same family significantly affected the CCR workload estimates. The following figure shows an estimate of the FSDD considering two products within the same family. Both products use an average processing time to calculate the workload. Product 1 represents the case when the average estimate is similar to the real value of the processing time. Product 2 is used to represent the two types of mistakes that result in inaccurate estimates. The Figure 5.3b shows one of the most critical effects of using an inaccurate average estimation method. Here, underestimating the processing time leads the plant to promise orders within a period that it is not capable of achieving. In contrast according to the presented in figure 5.3C overestimating the real processing time does not harm the DDP but could cause periods of time that the CCR will be idle losing the opportunity of generating an additional sale.

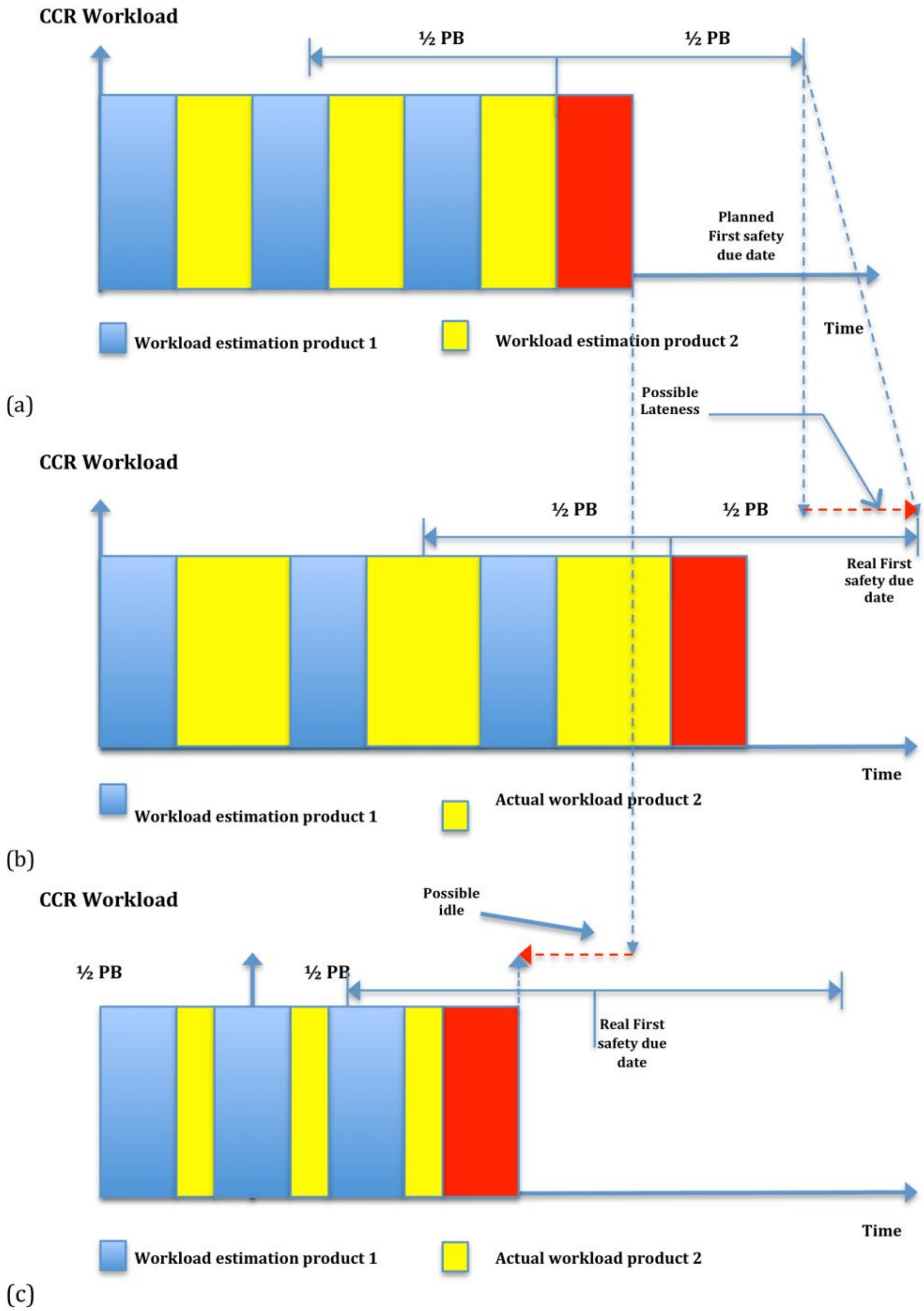


Figure 5.3: First safety due date estimation

(a) First safety due date estimation method for two products within the same family assuming an average processing time estimation method. (b) First safety due date estimation method for two products within the same family assuming that the average processing times underestimate the actual processing time at the CCR. (c) First safety due date estimation method for two products within the same family assuming that the average processing times overestimate the actual processing time at the CCR.

In this study, we propose the incorporation of a throughput diagram, which is a tool proposed by Wiendahl (1988) that uses curves to illustrate the input and output of orders on the shop floor. The primary ability of this tool is to graphically depict information in a way that shows the real flow of a workplace. Previous work has used TH diagrams as part of the workload control (WLC) methodology. In such cases, its objective has been oriented to monitor the lead time of orders, which is one of the primary focal points of the WLC methodology (G. Soepenberg, Land, & Gaalman, 2012).

The TH diagram is a graphic traditionally composed of a combination of input and output curves. The former considers the initial inventory and the accumulation of entered orders, with work content expressed in standard hours. Similarly, the output curve is plotted by cumulatively entering completed orders expressed in the same time units.

The final result is Figure 5.4 in which the distance between the input and output curves corresponds to the WIP level in the CCR at time *t* (Lödding & Lödding, 2013). In an FCFS environment, the horizontal length between the input and output curve corresponds to the lead times (G. D. Soepenberg, 2010).

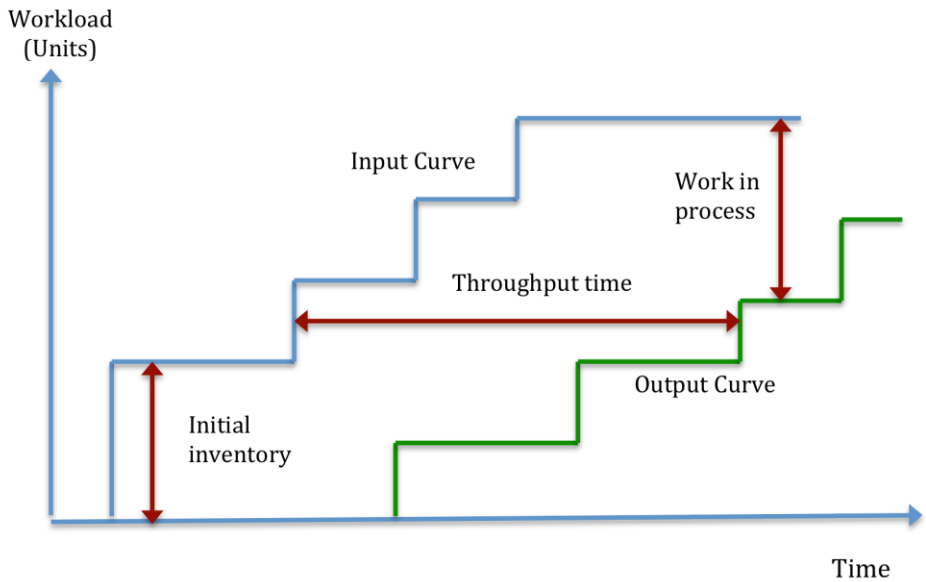


Figure 5.4: Throughput diagram

Similar to the WLC methodology, we propose incorporating the TH diagram as a mechanism to monitor order lead times by incorporating the composition of the CCR workload. In this way, the diagram can be used to contrast divergences between the real and expected lead times while considering the composition of orders that comprise the queue in front of the CCR. The divergences found using the TH diagram can be used to make necessary adjustments to the CCR processing time estimates.

Before explaining the TH diagram application, it is necessary to understand that this application is no more than analysing a simple queue system comprised of only one workstation, i.e., the CCRs in the case. The objective is to determine whether the lead time required to go through the queue and be served at the CCR is similar to the expected time. Henceforth, this time will be called the throughput time.

The throughput diagram only includes orders that have previously arrived at the CCR queue; consequently, the throughput time of order *i* is composed of the processing times of the *i-1* other orders plus the processing time of order *i*. Considering only the direct load avoids any effect that would be transmitted from previous stages to the CCR station. Therefore, any difference between the expected and real throughput times can be related to 1) an inaccurate processing time estimate or 2) external factors that delayed or accelerated the process at the CCR.

Furthermore, focusing on the CCR for the application of the throughput diagram is in accordance with the TOC methodology, which considers it critical to monitor the weakest link in a chain of events (Cox III & Spencer, 1998). However, its application is not solely restricted to the actual CCR but also to all resources that can potentially limit the capacity of a particular system.

Throughput diagram application for monitoring the accuracy of CCR processing time estimates.

The primary purpose of including a throughput diagram is to provide S-DBR practitioners with a mechanism for monitoring throughput times at the critical workstations (CCRs). Consequently, the mechanism should be visual and allow for a quick recognition of the differences that imply a change in the CCR processing time estimates.

Furthermore, it is necessary for the input and output curves to be expressed in units and not in standard hours. The reason is because the aim of the tool is to determine whether the CCR time estimates have the necessary precision. It would be a mistake to begin the analysis using the time estimation that we intend to test.

After considering the aforementioned changes, the following describe the necessary steps for applying the TH diagram to evaluate the CCR processing time estimates:

1) Plot the input curve considering orders already in the queue or in process at a workstation as part of the starting inventory. Subsequently, the arrivals should be plotted on a cumulative curve. Any additional step in the curve should be related to the arrival of orders at the CCR queue.
2) Include complementary information that represents the composition of orders that comprise the cumulative input of work. Expressed in units, it will show the different products associated with the CCR world.
3) Include the output curve that represents the completion of jobs as a function of time. In the FCFCS environment that is most commonly found in S-DBR implementations, the horizontal length between the input and output curves indicates the required time for completing a process for a specific direct load at the CCR.
4) Include a theoretical output curve that should be created according to the expected throughput time based on the CCR processing time estimates. According to figure 5.5 it is suggested that the output curve be plotted relative to the input curve. As a result, it is easy to determine the relationship between the direct load at the CCR and its real or expected throughput time.

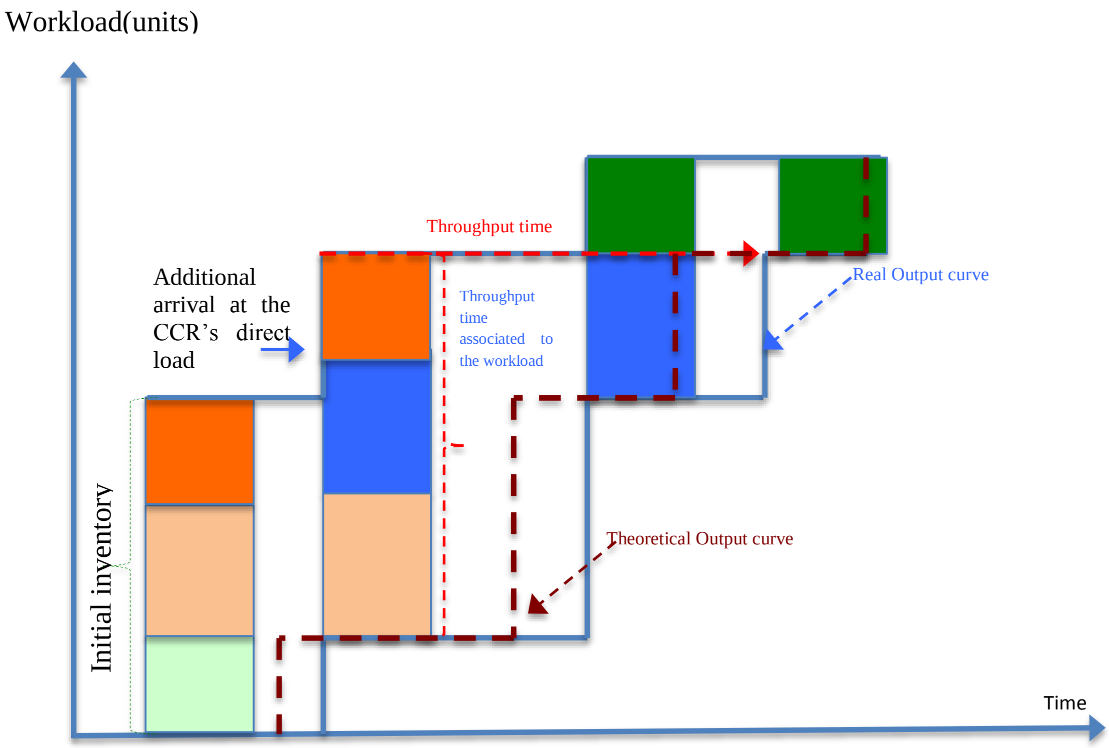


Figure 5.5: Throughput diagram application for controlling processing time estimates

5) Determine positive or negative differences between the theoretical and real output curves. Analyse the causes of these differences according to the proposed patterns in Figure 5.6. Each pattern represents a group of potential causes and suggests some action plans that should be considered to obtain more accurate throughput time estimates.

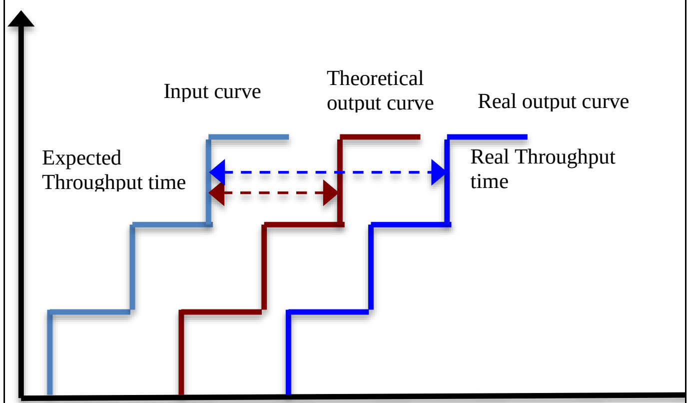
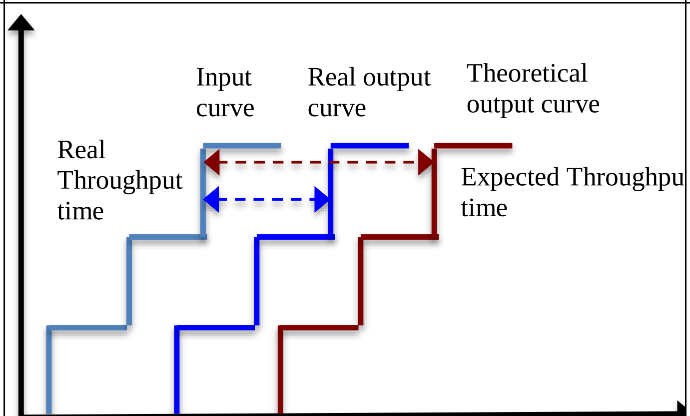
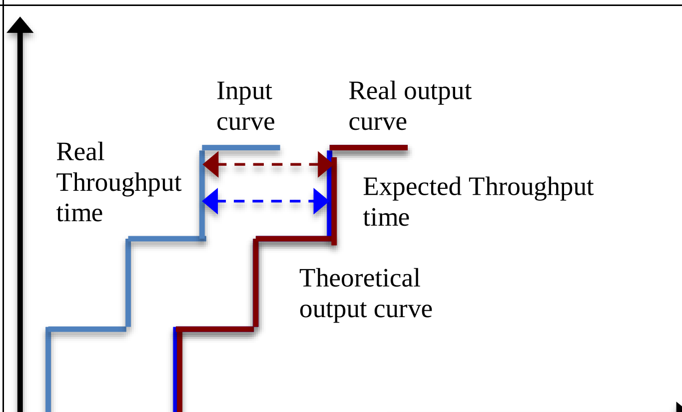
Pattern Name	Graphical Pattern	Potential causes	Action Plan
Lagging Pattern		▪ Underestimated processing time ▪ Reduction of performance ▪ Excessive setup adjustments ▪ Breakdowns	Evaluate the accuracy of the processing times for products within each family. Evaluate the causes of the reduced speed or generation of minor stoppages. Evaluate the relationship between the setup and the sequence of parts. Determine the causes of equipment breakdowns.
Leading Pattern		▪ Overestimated processing times ▪ Increase in performance	Evaluate the accuracy of the processing times for products within each family. Evaluate the causes of the increased speed.
Pattern Name	**Graphical Pattern**	**Potential causes**	**Action Plan**
No discrepancy		▪ Appropriate processing time estimate	Maintain the processing time estimates.

Figure 5.6: Possible patterns observed during the throughput diagram analysis

5.1.4 POOGI. Elaborating projects to improve non-constrained resources can be beneficial for overall operational performance.

The theory of constraint (TOC) is primarily focused on identifying and improving the aspects that hinder the achievement of a system's goals. Initiatives related to *exploiting* and *expanding* the constraints are aimed to reduce the influence of the constraints with respect to the performance of an entire system. However, they have noticeable differences. For example, the exploiting step is aimed at maximising the performance without a significant increase in resources. In this case, initiatives such as reducing breakdowns, minimising setup times or procuring only the needed products should not require a large investment. However, expanding a system's constraint may by very expensive, considering that it is associated with different initiatives, such as hiring additional people, acquiring equipment or making significant modifications that demand high capital expenditures.

In this context, the experiences obtained from the real S-DBR applications have shown that companies are more oriented to expanding than exploiting system constraints. Certainly, this is not a signal of the economical welfare of SMEs but an indication of their poor continuous improvement systems. It is easier to acquire a new item than to improve the performance of the original piece of equipment. However, in many cases, expanding the CCRs is physically or economically impractical. Consequently, companies postpone the actions required to expand the capacity of the CCRs, which significantly affects their operational performance. Precisely at this point, companies encounter the dilemma of whether it is advisable to take measures to expand the capacity of other resources despite these resources not being considered internal constraints.

This topic has been discussed by several authors, such as Hopp and Spearman (2008), who used a TH versus WIP curve to examine the impact of improving the capacity of resources not considered to be internal constraints. Using a simple experiment with a line of four single machine stations, the authors expanding the capacity of all resources except the internal constraint. The result presented in Figure 5.7 was a significant increment at the TH for any WIP level.

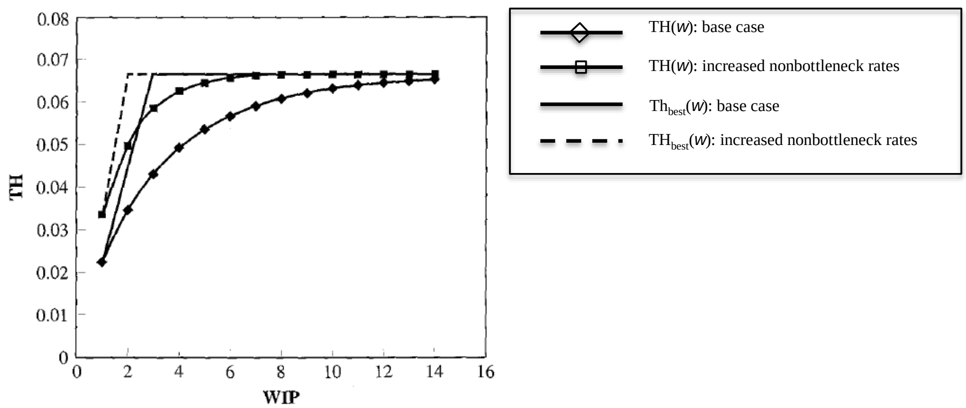


Figure 5.7: Change in TH curve due to an increase in the rate of non-bottlenecks.

Source: Hopp and Spearman, 2008

Although the increase was greater for small WIP levels compared with larger values, the results suggest that improvements at non-constrained resources are still a good option for improving overall operational performance. Similarly, Ignizio (2009) presented a case in which an increase in the throughput capacity of a line should not necessarily be restricted to the CCR to obtain the maximum operational performance. Considering these findings, it is important that S-DBR incorporates procedures specifically designed for cases in which expanding or exploiting the CCR is technically or economically infeasible.

6

Conclusions and Future Research

6.1 Concluding Remarks

Considering that an inappropriate selection of a PPC can have a significant effect on the performance of manufacturing companies, this doctoral research proposes selecting a methodology that is suitable for the characteristics of SMEs. The focus on this specific group of industries responds to the critical consequences that an inappropriate determination of PPCs can have on SMEs, particularly due to their limited access to financial resources. As a result, it was necessary to establish a framework for the operative mechanisms of PPCs and their relationship with the market and product dimensions. Considering Ecuadorian SMEs as a sample group, it was possible to identify S-DBR as the most suitable option for application in the SME environment. Using a case study methodology, empirical evidence was collected to assess the appropriateness of this PPC system for the characteristics of Ecuadorian SMEs, which are generally shared with the majority of SMEs around the world. Finally, a group of enhancements is proposed for the S-DBR methodology. These enhancements were determined by contrasting the standard S-DBR implementation methodology with the operative and market characteristics included in the case study. In this section, we review the primary research questions and provide answers based on the findings presented in the previous chapters.

1. **Which factors significantly influence the selection of a PPC?**

   Chapter 2 presents a review of the literature regarding the previous frameworks used to select or design PPCs. Although numerous proposals have been presented, there is a lack of frameworks that incorporate the product and process dimensions in conjunction with market requirements, focusing primarily on a quantitative approach. In this study, based on a literature review, we propose a framework that incorporates the dimensions considered to be highly significant in the characterisation of SMEs and that are directly related to the operation of PPCs. Our framework incorporates several product dimensions, such as the product mix variation, level of customisation, product mix and product structure. The process dimensions included are the process pattern, production information availability, level of training, processing time variability and setup time correlation. Finally, the market requirements considered important for the SME characterisation include the order winner, volume demand variability, inter-arrival time variability, due date tightness and variability of the due date allowance. To test this particular combination of quantitative and qualitative measures, we apply our proposed framework to determine a suitable PPC for Ecuadorian SMEs. The results not only show the influence of the previous dimensions on the optimal suggestion with respect to the suitability of the evaluated PPCs but also provide the strengths and weaknesses of each PPC system with respect to the evaluated dimensions. This information provides practical insights by providing practitioners with a quantitative measure of the opportunities for a PPC within their company.

2. How are SMEs characterised in terms of each dimension considered to be critical for the selection of a PPCs?

Using Ecuadorian SMEs as a sample, this study categorised SMEs in terms of each dimension proposed in the framework for selecting a PPCs. As a result, the necessary data were collected from three information sources: (a) governmental offices, such as the National Institute of Statistics and Censes (INEC), and non-governmental organisations, such as the Institute of Socio Economical and Technological Investigations (INSOTEC); (b) a survey administered in 2008 to 117 Ecuadorian SMEs; and (c) in-depth interviews of 21 manufacturing Ecuadorian SMEs. The results were found to be similar to the characteristics generally cited for a typical SME involved in an MTO environment. The moderate and high variability in demand resulted from the significant influence of the customer, which is typically a large company or an important economical group. Similarly, trying to satisfy the requirements of a highly competitive environment, an SME must significantly diversify the variety of its products, which can typically be categorised as simple products. Finally, the production systems of SMEs are characterised by highly variable processes comprised of unskilled operators and a deficient application of IT systems. Another characteristic that was revealed was the simplicity of the process, usually with sequence-independent setup times and customisation reserved to no more than two workstations in an SME's production system.

3. Which PPC system is most suitable according to the SME characteristics?

According to our proposed framework and a comparison of the Ecuadorian SME characterisation with the main principles of some classical PPCs, it was possible to identify S-DBR as the most suitable system for Ecuadorian SMEs. This result can be generalised considering the similarity between the characteristics of Ecuadorian SMEs and the characterisation of general SMEs around the world. The suitability of S-DBR can be justified by its primary approach to MTO environments, with the necessary implications related to product variability and the presence of non-fixed routing for operational processes. Additionally, the simplicity of this system, resulting from maintaining only one buffer and the lack of detailed CCR scheduling, makes S-DBR a flexible option for environments in which new products are frequently added, such as that of SMEs. Another positive factor was the simplicity of the Ecuadorian SMEs' products, which do not require numerous assembly points that could act as a barrier in the implementation of the S-DBR methodology. Finally, the simplicity of the mechanisms proposed by the S-DBR methodology makes this system recommendable for companies that are not accustom to maintaining highly sophisticated IT systems and highly skilled workers.

The main contribution of this study has been the proposed framework for the design or selection of a PPC, providing a quantitative indicator of the level of suitability of a given PPC with respect to a company's characteristics. Additionally, this framework is a practical tool for obtaining valuable insights with respect to the weaknesses or strengths of a particular PPC and with respect to the characteristics of a company. This framework is a valuable contribution in that it provides a particular combination of quantitative and qualitative measures that are directly related to the operational aspect of PPCs. For example, our proposed framework demonstrates that processing times with a coefficient of variation exceeding 1 can negatively influence the proportion of backordered demands or significantly reduce the production capacity of a Kanban system. Similarly, using the due date allowance as a dimension allows the determination of a negative branch that can appear in a PPC when slack times are limited. In addition, the framework was applied by considering the products, process characteristics and market requirements of Ecuadorian SMEs. The results also represent an important contribution to practitioners because they can be used to determine a PPC system that is highly suitable for the variable characteristics of Ecuadorian SMEs. Using a case study approach for four companies, it was possible to explore the practical issues related to the S-DBR implementation. The case analysis within this study first identified the choices made in during the implementation within the four companies according to their process and product characteristics. The cross-case analysis explored the effects of the S-DBR implementation on a group of performance measures. The findings presented herein provide new insights into the S-DBR implementation process in the context of SMEs and the effects of this approach on performance measures. Finally, this study explored opportunities for improving S-DBR through an analysis of the empirical evidence obtained in the case study.

6.2 Future Research

The proposed framework for selecting or designing a PPC has been presented as a practical application aimed to evaluate the most suitable PPCs among five classical approaches: MRP, Kanban, WLC, DBR and S-DBR. A future study could strive to determine the applicability of this framework in the design process and propose refinements with respect to a specific PPC methodology. Although this framework provides the strengths and weaknesses of PPCs for each of the evaluated dimensions, an evaluation of this tool as part of the recurring process of improving a PPC according to a company's characteristics was not conducted.

Additionally, citing S-DBR as the most suitable PPCs for the characteristics of Ecuadorian SMEs does not mean that this system does not exhibit improvement opportunities. In fact, future research could directly be aimed at evaluating enhancements to the proposed S-DBR methodology. Based on the empirical evidence collected through the case study, we present several topics that could be investigated in future research. For example, having identified that the positive operational impact of controlling the release order is not exclusively attributed to the S-DBR step that requires setting the buffer time to half of the current lead time, different release techniques could be evaluated under a S-DBR implementation context. Another recommendation for future research is associated with the proposal and evaluation of methodologies that provide statistical evidence to demonstrate that companies have reached the required service level. With respect to the location of the CCR, this study has presented a limitation in evaluating the mechanism proposed by Lee et al. (2010) for determining due date commitments when the CCR is located at the back stage of the routing. In future research, at least one example is desirable to confirm the effectiveness of an alternative mechanism based on this scenario.

Additionally, considering that inaccurately estimated CCR processing times can result in significant delays in meeting due dates or excessive idle times in the CCR, it is necessary explore the application of alternative mechanisms, such as visual tools that may offer real-time information with respect to the accuracy of CCR processing time estimates. Finally, future studies could analyse the operational impact of expanding the capacity in non-constrained workstations. Determining the appropriate environmental conditions for expanding the capacity of non-constrained workstations could provide practitioners with a guide for increasing the effectiveness of S-DBR without requiring high capital expenditures.

References

Abuhilal, L., Rabadi, G., & Sousa-Poza, A. (2006). Supply Chain Inventory Control: A Comparison Among JIT, MRP, and MRP With Information Sharing Using Simulation. *Engineering Management Journal, 18*(2).

Ahmad, N., & Qiu, R. G. (2009). Integrated model of operations effectiveness of small to medium-sized manufacturing enterprises. *Journal of Intelligent Manufacturing, 20*(1), 79-89.

Ajoku, P. N. (2007). Combining Lean Initiatives with Theory of Constraints in Distributed Product Design Chain Management. *IJEBM, 5*(2), 81-92.

Akturk, M., & Erhun, F. (1999). An overview of design and operational issues of kanban systems. *International Journal of Production Research, 37*(17), 3859-3881.

Atwater, J. B., & Chakravorty, S. S. (2002). A STUDY OF THE UTILIZATION OF CAPACITY CONSTRAINED RESOURCES IN DRUM- BUFFER- ROPE SYSTEMS*. *Production and Operations Management, 11*(2), 259-273.

Barratt, M., Choi, T. Y., & Li, M. (2011). Qualitative case studies in operations management: trends, research outcomes, and future research implications. *Journal of Operations Management, 29*(4), 329-342.

Baykoç, Ö. F., & Erol, S. (1998). Simulation modelling and analysis of a JIT production system. *International Journal of Production Economics, 55*(2), 203-212.

Baynat, B., Dallery, Y., Mascolo, M. D., & Frein, Y. (2001). A multi-class approximation technique for the analysis of kanban-like control systems. *International Journal of Production Research, 39*(2), 307-328.

Benton, W. (1991). Safety stock and service levels in periodic review inventory systems. *Journal of the Operational Research Society*, 1087-1095.

Benton, W., & Shin, H. (1998). Manufacturing planning and control: The evolution of MRP and JIT integration. *European Journal of Operational Research, 110*(3), 411-440.

Berry, W. L., & Hill, T. (1992). Linking systems to strategy. *International journal of operations & production management, 12*(10), 3-15.

Bertrand, J., & Muntslag, D. (1993). Production control in engineer-to-order firms. *International Journal of Production Economics, 30*, 3-22.

Betterton, C. E., & 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*(1), 66-79.

Betterton, C. E., & Cox, J. F. (2009). Espoused drum-buffer-rope flow control in serial lines: A comparative study of simulation models. *International Journal of Production Economics, 117*(1), 66-79.

Bonney, M. (2000). Reflections on production planning and control (PPC). *Gestão & produção, 7*(3), 181-207.

Bonvik, A. M., Couch, C., & Gershwin, S. B. (1997). A comparison of production-line control mechanisms. *International Journal of Production Research, 35*(3), 789-804.

Boonlertvanich, K. (2005). Extended-CONWIP-Kanban system: control and performance analysis.

Bortolotti, T., Danese, P., & Romano, P. (2013). Assessing the impact of just-in-time on operational performance at varying degrees of repetitiveness. *International Journal of Production Research, 51*(4), 1117-1130.

Breyfogle III, F. W. (2003). *Implementing six sigma: smarter solutions using statistical methods*: John Wiley & Sons.

Burbidge, J. L. (1978). *The principles of production control*: Macdonald and Evans.

Burton-Houle, T. (2001). The theory of constraints and its thinking processes. *Documento WWW. URL www. goldratt. com, editor. Goldratt Institute*.

Chakravorty, S. S. (2001). An evaluation of the DBR control mechanism in a job shop environment. *Omega, 29*(4), 335-342.

Chakravorty, S. S., & Atwater, J. B. (2005). The impact of free goods on the performance of drum-buffer-rope scheduling systems. *International Journal of Production Economics, 95*(3), 347-357.

Chang, T.-M., & Yih, Y. (1994). Generic kanban systems for dynamic environments. *THE INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH, 32*(4), 889-902.

Chang, Y.-C., & Huang, W.-T. (2011). Using simplified drum-buffer-rope for re-entrant flow shop scheduling in a random environment. *African Journal of Business Management, 5*(26), 10796-10810.

CHATURVEDI, M., & GOLHAR, D. Y. (1992). Simulation modelling and analysis of a JIT production system. *Production Planning & Control, 3*(1), 81-92.

Chaudhury, A., & Whinston, A. B. (1990). Towards an adaptive Kanban system. *THE INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH, 28*(3), 437-458.

Chen, Y., Miao, W.-M., Lin, Z.-Q., & Chen, G.-L. (2008). Adjusting MRP for dynamic differentiation of identical items for process customisation. *Production Planning and Control, 19*(6), 616-626.

Choudhari, S. C., Adil, G. K., & Ananthakumar, U. (2012). Choices in manufacturing strategy decision areas in batch production system–six case studies. *International Journal of Production Research, 50*(14), 3698-3717.

Chung, S.-H., Yang, M.-H., & Cheng, C.-M. (1997). The design of due date assignment model and the determination of flow time control parameters for the wafer fabrication factories. *Components, Packaging, and Manufacturing Technology, Part C, IEEE Transactions on, 20*(4), 278-287.

Cigolini, R., Perona, M., & Portioli, A. (1998). Comparison of order review and release techniques in a dynamic and uncertain job shop environment. *International Journal of Production Research, 36*(11), 2931-2951.

Corbett, T., & Csillag, J. M. (2001). Analysis of the effects of seven drum-buffer-rope implementations. *Production and Inventory Management Journal, 42*(3/4), 17-23.

Corsten, H., Gössinger, R., & Wolf, N. (2005). Flexibility-driven order releases in job-shop production. *Technovation, 25*(8), 815-830.

Cox III, J. F., & Spencer, M. S. (1998). *The constraints management handbook* (Vol. 3): CRC Press.

Cox, J. F., Blackstone, J. H., & Spencer, M. S. (1995). *APICS dictionary*.

Davis, W. J., & STUBITZ, S. J. (1987). Configuring a kanban system using a discrete optimization of multiple stochastic responses. *International Journal of Production Research, 25*(5), 721-740.

Dean, P., Tu, Y., & Xue, D. (2009). An information system for one-of-a-kind production. *International Journal of Production Research, 47*(4), 1071-1087.

Deleersnyder, J.-L., Hodgson, T. J., Muller-Malek, H., & O'Grady, P. J. (1989). Kanban controlled pull systems: an analytic approach. *Management science, 35*(9), 1079-1091.

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory building from cases: opportunities and challenges. *Academy of management journal, 50*(1), 25-32.

Eivazy, H., Rabbani, M., & Ebadian, M. (2009). A developed production control and scheduling model in the semiconductor manufacturing systems with hybrid make-to-stock/make-to-order products. *The International Journal of Advanced Manufacturing Technology, 45*(9-10), 968-986.

Enns, S. (2001). MRP performance effects due to lot size and planned lead time settings. *International Journal of Production Research, 39*(3), 461-480.

Enns, S. (2002). MRP performance effects due to forecast bias and demand uncertainty. *European Journal of Operational Research, 138*(1), 87-102.

Fernandes, N. O., & do Carmo-Silva, S. (2006). Generic POLCA—A production and materials flow control mechanism for quick response manufacturing. *International Journal of Production Economics, 104*(1), 74-84.

FINCH, B. R. J., & Cox, J. F. (1986). An examination of just-in-time management for the small manufacturer: with an illustration. *International Journal of Production Research, 24*(2), 329-342.

Fisher, M. L., & Ittner, C. D. (1999). The impact of product variety on automobile assembly operations: Empirical evidence and simulation analysis. *Management science, 45*(6), 771-786.

Fowler, J. W., Hogg, G. L., & Mason, S. J. (2002). Workload control in the semiconductor industry. *Production Planning & Control, 13*(7), 568-578.

Fry, T. D., Karwan, K. R., & Steele, D. C. (1991). Implementing drum-buffer-rope to control manufacturing lead time. *International Journal of Logistics Management, The, 2*(1), 12-18.

Gargeya, V., & Thompson, J. (1994). Just-in-time production in small job shops. *INDUSTRIAL MANAGEMENT-CHICAGO THEN ATLANTA-, 36*, 23-23.

Gaury, E., Kleijnen, J., & Pierreval, H. (2001). A methodology to customize pull control systems. *Journal of the Operational Research Society*, 789-799.

Gaury, E., Pierreval, H., & Kleijnen, J. (2000). An evolutionary approach to select a pull system among Kanban, Conwip and Hybrid. *Journal of Intelligent Manufacturing, 11*(2), 157-167.

Georgiadis, P., & Politou, A. (2013). Dynamic Drum-Buffer-Rope Approach for Production Planning and Control in Capacitated Flow-shop Manufacturing Systems. *Computers & Industrial Engineering*.

Goldratt, E. (2006). Reliable rapid response strategy and tactics tree. *Goldratt's Group*.

Goldratt, E., Goldratt, R., & Abramov, E. (2002). Strategy and tactics. *Goldratt Consulting*.

Goldratt, E. M. (1990). *Theory of constraints*: North River.

Goldratt, E. M., & Cox, J. (2005). A Process of Ongoing Improvement. *Journal of Manufacturing Technology Management*, *16*(3), 302.

Goldratt, E. M., Schragenheim, E., & Ptak, C. A. (2000). *Necessary but not sufficient: a theory of constraints business novel*: North River Press.

Gonzalez-R, P. L., Framinan, J. M., & Ruiz-Usano, R. (2010). A multi-objective comparison of dispatching rules in a drum–buffer–rope production control system. *International Journal of Computer Integrated Manufacturing, 23*(2), 155-167.

Guide Jr, V. (1996). Scheduling using drum-buffer-rope in a remanufacturing environment. *International Journal of Production Research, 34*(4), 1081-1091.

Guo, Y.-h., & Qian, X.-s. (2006). Shop floor control in wafer fabrication based on drum-buffer-rope theory. *COMPUTER INTEGRATED MANUFACTURING SYSTEMS-BEIJING-*, *12*(1), 111.

Gupta, M., Ko, H.-J., & Min, H. (2002). TOC-based performance measures and five focusing steps in a job-shop manufacturing environment. *International Journal of Production Research, 40*(4), 907-930.

Gupta, M., & Snyder, D. (2009). Comparing TOC with MRP and JIT: a literature review. *International Journal of Production Research, 47*(13), 3705-3739.

Gupta, S. M., & Al-Turki, Y. A. (1997). An algorithm to dynamically adjust the number of kanbans in stochastic processing times and variable demand environment. *Production Planning & Control*, *8*(2), 133-141.

Hadas, L., Cyplik, P., & Fertsch, M. (2009). Method of buffering critical resources in make-to-order shop floor control in manufacturing complex products. *International Journal of Production Research, 47*(8), 2125-2139.

Hayes, R. H., & Wheelwright, S. C. (1984). Restoring our competitive edge: competing through manufacturing.

Hendry, L., Kingsman, B., & Cheung, P. (1998). The effect of workload control (WLC) on performance in make-to-order companies. *Journal of Operations Management, 16*(1), 63-75.

Hendry, L., Land, M., Stevenson, M., & Gaalman, G. (2008). Investigating implementation issues for workload control (WLC): a comparative case study analysis. *International Journal of Production Economics, 112*(1), 452-469.

Henrich, P. (2005). *Applicability aspects of workload control in job shop production*: Labyrint Publications.

Henrich, P., Land, M., & Gaalman, G. (2004). Exploring applicability of the workload control concept. *International Journal of Production Economics, 90*(2), 187-198.

Hill, T. (2000). Manufacturing Strategy-Text and Cases. 2000. *Irvin McGrave Hill.–68c*.

Ho, J. C., & Chang, Y.-L. (2001). An integrated MRP and JIT framework. *Computers & Industrial Engineering, 41*(2), 173-185.

Hoeck, M. (2008). A workload control procedure for an FMC integrated in a job shop. *International Journal of Computer Integrated Manufacturing, 21*(6), 666-675.

Hopp, W. J., & Spearman, M. L. (1993). Setting safety leadtimes for purchased components in assembly systems. *IIE transactions, 25*(2), 2-11.

Hopp, W. J., & Spearman, M. L. (2008). *Factory physics* (Vol. 2): McGraw-Hill/Irwin New York.

Howard, A., Kochhar, A., & Dilworth, J. (2000). Case studies based development of a rule-base for the specification of manufacturing planning and control systems. *International Journal of Production Research, 38*(12), 2591-2606.

Huq, Z. (1999). Conventional shop control procedures to approximate JIT inventory performance in a job shop. *Journal of manufacturing systems, 18*(3), 161-174.

Hurley, S. F., & Kadipasaoglu, S. (1998). Wandering bottlenecks: speculating on the true causes. *Production and Inventory Management Journal, 39*, 1-4.

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

Ignizio, J. (2009). Optimizing factory performance: New York, McGraw-Hill.

Jodlbauer, H., & Huber, A. (2008). Service-level performance of MRP, kanban, CONWIP and DBR due to parameter stability and environmental robustness. *International Journal of Production Research, 46*(8), 2179-2195.

Johnson, L. A., & Montgomery, D. C. (1974). *Operations research in production planning, scheduling, and inventory control* (Vol. 6): Wiley New York.

Kadipasaoglu, S. N., Xiang, W., Hurley, S. F., & Khumawala, B. M. (2000). A study on the effect of the extent and location of protective capacity in flow systems. *International Journal of Production Economics, 63*(3), 217-228.

Kagan, A., Lau, K., & Nusgart, K. R. (1990). Information system usage within small business firms. *Entrepreneurship: Theory and Practice, 14*(3), 25-37.

Klusewitz, G., & Rerick, R. (1996). *Constraint management through the drum-buffer-rope system.* Paper presented at the Advanced Semiconductor Manufacturing Conference and Workshop, 1996. ASMC 96 Proceedings. IEEE/SEMI 1996.

Kochhar, A., & McGarrie, B. (1992). Identification of the Requirements of Manufacturing Control Systems: A Key Charactericstics Approach. *Integrated Manufacturing Systems, 3*(4), 4-15.

Koh, S.-G., & Bulfin, R. L. (2004). Comparison of DBR with CONWIP in an unbalanced production line with three stations. *International Journal of Production Research, 42*(2), 391-404.

Koh, S. L., Saad, S. M., & Padmore, J. (2004). Development and implementation of a generic order release scheme for modelling MRP-controlled finite-capacitated manufacturing environments. *International Journal of Computer Integrated Manufacturing, 17*(6), 561-576.

Koukoumialos, S., & Liberopoulos, G. (2006). An analytical method for the performance evaluation of echelon kanban control systems *Stochastic Modeling of Manufacturing Systems* (pp. 193-222): Springer.

Krajewski, L. J., King, B. E., Ritzman, L. P., & Wong, D. S. (1987). Kanban, MRP, and shaping the manufacturing environment. *Management science, 33*(1), 39-57.

Krieg, G. N., & Kuhn, H. (2004). Analysis of multi-product kanban systems with state-dependent setups and lost sales. *Annals of Operations Research, 125*(1-4), 141-166.

Land, M. (2006). Parameters and sensitivity in workload control. *International Journal of Production Economics, 104*(2), 625-638.

Land, M., & Gaalman, G. (1996). Workload control concepts in job shops a critical assessment. *International Journal of Production Economics, 46*, 535-548.

Land, M. J. (2004). *Workload control in job shops, grasping the tap*: University Library Groningen][Host].

Lane, G., & Shook, J. (2007). *Made-to-order Lean: Excelling in a High-mix, Low-volume Environment*: Productivity Pr.

Larsen, N., & Alting, L. (1993). Criteria for selecting a production control philosophy. *Production Planning & Control, 4*(1), 54-68.

Lee, C. Y. (1993). A recent development of the integrated manufacturing system: a hybrid of MRP and JIT. *International journal of operations & production management, 13*(4), 3-17.

Lee, J.-H., Chang, J.-G., Tsai, C.-H., & Li, R.-K. (2010). Research on enhancement of TOC Simplified Drum-Buffer-Rope system using novel generic procedures. *Expert Systems with Applications, 37*(5), 3747-3754.

Lee, J.-H., Hwang, Y. J., Wang, M.-T., & Li, R. K. (2009). Why Is High Due-Date Performance So Difficult to Achieve?—An Experimental Study. *Production and Inventory Management Journal, 45*(1), 30-43.

Leonard-Barton, D. (1990). A dual methodology for case studies: synergistic use of a longitudinal single site with replicated multiple sites. *Organization science, 1*(3), 248-266.

Lödding, H., & Lödding, H. (2013). Decentralized WIP Oriented Manufacturing Control. *Handbook of Manufacturing Control: Fundamentals, description, configuration*, 435-452.

Luh, P. B., Zhou, X., & Tomastik, R. N. (2000). An effective method to reduce inventory in job shops. *Robotics and Automation, IEEE Transactions on, 16*(4), 420-424.

Mabin, V. J., & 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), 568-595.

MacCarthy, B., Wilson, J., & Crawford, S. (2001). Human performance in industrial scheduling: a framework for understanding. *Human Factors and Ergonomics in Manufacturing & Service Industries, 11*(4), 299-320.

MacCarthy, B. L., & Fernandes, F. C. (2000). A multi-dimensional classification of production systems for the design and selection of production planning and control systems. *Production Planning & Control, 11*(5), 481-496.

Mallick, R. W., & Gaudreau, A. T. (1951). *Plant Layout*: Wiley.

Marek, R. P., Elkins, D. A., & Smith, D. R. (2001). *Manufacturing controls: understanding the fundamentals of Kanban and CONWIP pull systems using simulation.* Paper presented at the Proceedings of the 33nd conference on Winter simulation.

Mascolo, M. D., Frein, Y., & Dallery, Y. (1996). An analytical method for performance evaluation of kanban controlled production systems. *Operations Research, 44*(1), 50-64.

Mbaya, M. M. N. (2000). *The constraints and limitations of manufacturing resource planning (MRP II) as a tool for shop floor control.* Massachusetts Institute of Technology.

McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of Operations Management, 11*(3), 239-256.

Meredith, J. (1998). Building operations management theory through case and field research. *Journal of Operations Management, 16*(4), 441-454.

Mills, A. J. (2010). *Encyclopedia of Case Study Research* (Vol. 1): Sage.

Missbauer, H. (1997). Order release and sequence-dependent setup times. *International Journal of Production Economics, 49*(2), 131-143.

Modarress, B., Ansari, A., & Willis, G. (2000). Controlled production planning for Just-In-Time short-run suppliers. *International Journal of Production Research, 38*(5), 1163-1182.

Montgomery, D. C. (2007). *Introduction to statistical quality control*: John Wiley & Sons.

Nahmias, S., & Cheng, Y. (2009). *Production and operations analysis* (Vol. 5): McGraw-Hill New York.

Newman, W. R., & Sridharan, V. (1995). Linking manufacturing planning and control to the manufacturing environment. *Integrated Manufacturing Systems, 6*(4), 36-42.

Olhager, J., & Rudberg, M. (2002). Linking manufacturing strategy decisions on process choice with manufacturing planning and control systems. *International Journal of Production Research, 40*(10), 2335-2351.

Olhager, J., & Wikner, J. (2000). Production planning and control tools. *Production Planning & Control, 11*(3), 210-222.

Panizzolo, R., & Garengo, P. (2013). Using Theory of Constraints to Control Manufacturing Systems: A Conceptual Model. *Industrial Engineering & Management*.

Park, C., Song, J., Kim, J.-G., & Kim, I. (1999). Delivery date decision support system for the large scale make-to-order manufacturing companies: a Korean electric motor company case. *Production Planning & Control, 10*(6), 585-597.

Patti, A. L., Watson, K., & Blackstone Jr, J. H. (2008). The shape of protective capacity in unbalanced production systems with unplanned machine downtime. *Production Planning and Control, 19*(5), 486-494.

Petroni, A. (2002). Critical factors of MRP implementation in small and medium-sized firms. *International journal of operations & production management, 22*(3), 329-348.

Petroni, A., & Rizzi, A. (2001). Antecedents of MRP adoption in small and medium-sized firms. *Benchmarking: An International Journal, 8*(2), 144-156.

Ptak, C., & Smith, C. (2011). *Orlicky's Material Requirements Planning 3/E*: McGraw Hill Professional.

Qiao, F., & Wu, Q. (2013). Layered Drum-Buffer-Rope-Based Scheduling of Reentrant Manufacturing Systems. *IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING, 26*(2).

Rahman, S.-u. (1998). Theory of constraints: a review of the philosophy and its applications. *International journal of operations & production management, 18*(4), 336-355.

Riezebos, J., Korte, G., & Land, M. (2003). Improving a practical DBR buffering approach using Workload Control. *International Journal of Production Research, 41*(4), 699-712.

Rodríguez, M. E. V., Franco, T. C., & Vázquez, J. M. G. (1998). Alternativas para utilizar un sistema de control de la producción de tipo Kanban. *Investigaciones europeas de dirección y economía de la empresa, 4*(1), 101-116.

Roth, A. V. (2007). Applications of empirical science in manufacturing and service operations. *Manufacturing & Service Operations Management, 9*(4), 353-367.

Sabuncuoglu, I., & Karapınar, H. (1999). Analysis of order review/release problems in production systems. *International Journal of Production Economics, 62*(3), 259-279.

Sadat, S., Carter, M. W., & Golden, B. (2013). Theory of constraints for publicly funded health systems. *Health care management science, 16*(1), 62-74.

Schmitt, T. G., Klastorin, T., & Shtub, A. (1985). Production classification system: concepts, models and strategies. *International Journal of Production Research, 23*(3), 563-578.

Schragenheim, E. (2006). Using SDBR in rapid response projects. *Goldratt group*.

Schragenheim, E., & Dettmer, H. W. (2000a). *Manufacturing at warp speed: Optimizing supply chain financial performance*: CRC Press.

Schragenheim, E., & Dettmer, H. W. (2000b). Simplified Drum-Buffer-Rope A Whole System Approach to High Velocity Manufacturing. *WWW document) available, 29*, 2007.

Schragenheim, E., & Dettmer, H. W. (2000c). Simplified Drum-Buffer-Rope A Whole System Approach to High Velocity Manufacturing. *Goldratt Consulting, 29,* 2007.

Schragenheim, E., Dettmer, H. W., & PATTERSON, J. W. (2009a). Supply chain management at warp speed. *Supply chain management at warp speed*.

Schragenheim, E., Dettmer, H. W., & PATTERSON, J. W. (2009b). *Supply chain management at warp speed*.

Schragenheim, E., Dettmer, H. W., & Patterson, J. W. (2009c). *Supply chain management at warp speed: Integrating the system from end to end*: CRC Press Boca Raton, FL.

Schragenheim, E., & Ronen, B. (1989). *Buffer-management: A diagnostic tool for production control*: Tel Aviv University, Faculty of Management, Leon Recanati Graduate School of Business Administration.

Schragenheim, E., Weisenstern, A., & Schragenheim, A. (2006a). *What's really new in Simplified DBR.* Paper presented at the TOCICO international conference, Las Vegas, NV.

Schragenheim, E., Weisenstern, A., & Schragenheim, A. (2006b). *What's really new in Simplified DBR.* Paper presented at the TOCICO international conference, Las Vegas, NV.

Schroeder, D. M., Congden, S. W., & Gopinath, C. (1995). Linking competitive strategy and manufacturing process technology. *Journal of Management Studies, 32*(2), 163-189.

Scudder, G. D., & Hill, C. A. (1998). A review and classification of empirical research in operations management. *Journal of Operations Management, 16*(1), 91-101.

Silva, E. C. C. d., & Sacomano, J. B. (1995). Implantação de Kanban como técnica auxiliar do planejamento e controle da produção: um estudo de caso em fábrica de médio porte. *Gestão & produção, 2*(1), 59-70.

Silver, E. A., Pyke, D. F., & Peterson, R. (1998). *Inventory management and production planning and scheduling* (Vol. 3): Wiley New York.

Sirikrai, V., & Yenradee, P. (2006). Modified drum–buffer–rope scheduling mechanism for a non-identical parallel machine flow shop with processing-time variation. *International Journal of Production Research, 44*(17), 3509-3531.

Soepenberg, G., Land, M. J., & Gaalman, G. J. (2012). Workload control dynamics in practice. *International Journal of Production Research, 50*(2), 443-460.

Soepenberg, G. D. (2010). *Workload Control under Diagnosis*: University of Groningen.

Souza, F. B. d., & Pires, S. R. I. (2013). Making to availability: an application of the Theory of Constraints in make-to-stock environments. *Gestão & produção*(AHEAD), 0-0.

Spearman, M. L., Woodruff, D. L., & Hopp, W. J. (1990). CONWIP: a pull alternative to kanban. *THE INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH, 28*(5), 879-894.

Steele, D. C., Berry, W. L., & Chapman, S. N. (1995). Planning and Control in Multi- Cell Manufacturing. *Decision sciences, 26*(1), 1-34.

Steele*, D. C., Philipoom, P. R., Malhotra, M. K., & Fry, T. D. (2005). Comparisons between drum–buffer–rope and material requirements planning: a case study. *International Journal of Production Research, 43*(15), 3181-3208.

Stevenson, M. (2006). Refining a workload control (WLC) concept: a case study. *International Journal of Production Research, 44*(4), 767-790.

Stevenson, M., & Hendry, L. C. (2006). Aggregate load-oriented workload control: a review and a re-classification of a key approach. *International Journal of Production Economics, 104*(2), 676-693.

Stevenson, M., & Silva, C. (2008). Theoretical development of a workload control methodology: evidence from two case studies. *International Journal of Production Research, 46*(11), 3107-3131.

Stevenson*, M., Hendry, L. C., & Kingsman†, B. (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), 869-898.

Stuart, I., McCutcheon, D., Handfield, R., McLachlin, R., & Samson, D. (2002). Effective case research in operations management: a process perspective. *Journal of Operations Management, 20*(5), 419-433.

Sullivan, T. T., Reid, R. A., & Cartier, B. (2007). THE TOCICO DICTIONARY.

Tatsiopoulos, I., & Mekras, N. (1999). An expert system for the selection of production planning and control software packages. *Production Planning & Control, 10*(5), 414-425.

Tenhiala, A. (2011). Contingency theory of capacity planning: The link between process types and planning methods. *Journal of Operations Management, 29*(1), 65-77.

Towers, N., & Burnes, B. (2008). A composite framework of supply chain management and enterprise planning for small and medium-sized manufacturing enterprises. *Supply Chain Management: An International Journal, 13*(5), 349-355.

Tseng, M.-F., & Wu, H.-H. (2006). The study of an Easy-to-Use DBR and BM system. *International Journal of Production Research, 44*(8), 1449-1478.

Umble, M., Umble, E., & Murakami, S. (2006). Implementing theory of constraints in a traditional Japanese manufacturing environment: the case of Hitachi Tool Engineering. *International Journal of Production Research, 44*(10), 1863-1880.

Van Wezel, W., Van Donk, D. P., & Gaalman, G. (2006). The planning flexibility bottleneck in food processing industries. *Journal of Operations Management, 24*(3), 287-300.

Vollmann, T. (2005). Manufacturing Planning and Control for Supply Chain Manageme.

Vollmann, T. E., Berry, W. L., & Whybark, D. C. (1997a). Manufacturing planning and control systems. *Irwin, Boston*.

Vollmann, T. E., Berry, W. L., & Whybark, D. C. (1997b). Manufacturing planning and control systems, 1997. *Irwin, Boston*.

Vollmann, T. E., Berry, W. L., Whybark, D. C., & Jacobs, F. R. (2005). *Manufacturing planning and control for supply chain management*: McGraw-Hill/Irwin New York.

Wacker, J. G. (1998). A definition of theory: research guidelines for different theory-building research methods in operations management. *Journal of Operations Management, 16*(4), 361-385.

Wahlers, J. L., & Cox III, J. F. (1994). Competitive factors and performance measurement: applying the theory of constraints to meet customer needs. *International Journal of Production Economics, 37*(2), 229-240.

Watson, K., & Patti, A. (2008). A comparison of JIT and TOC buffering philosophies on system performance with unplanned machine downtime. *International Journal of Production Research, 46*(7), 1869-1885.

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*(2), 387-402.

Wiendahl, H.-P. (1995). *Load-oriented manufacturing control*: Springer.

Wiendahl, H.-P., & Tönshoff, K. (1988). The throughput diagram—An universal model for the illustration, control and supervision of logistic processes. *CIRP Annals-Manufacturing Technology, 37*(1), 465-468.

Wijngaard, J., & Wortmann, J. (1985). MRP and inventories. *European Journal of Operational Research, 20*(3), 281-293.

Wilson, F., Desmond, J., & Roberts, H. (1994). Success and failure of MRP II implementation. *British Journal of Management*, *5*(3), 221-240.

Wu, H.-H., Chen, C.-P., Tsai, C.-H., & Yang, C.-J. (2010). Simulation and scheduling implementation study of TFT-LCD Cell plants using Drum–Buffer–Rope system. *Expert Systems with Applications*, *37*(12), 8127-8133.

Wu, H.-H., & Liu, J.-Y. (2008). A capacity available-to-promise model for drum-buffer-rope systems. *International Journal of Production Research, 46*(8), 2255-2274.

Wu, S.-Y., Morris, J. S., & Gordon, T. M. (1994). A simulation analysis of the effectiveness of drum-buffer-rope scheduling in furniture manufacturing. *Computers & Industrial Engineering, 26*(4), 757-764.

Wysk, R. A., & Smith, J. S. (1995). A formal functional characterization of shop floor control. *Computers & Industrial Engineering, 28*(3), 631-643.

Yeung, J., Wong, W., & Ma, L. (1998). Parameters affecting the effectiveness of MRP systems: a review. *International Journal of Production Research, 36*(2), 313-332.

Yin, R. K. (2009). *Case study research: Design and methods* (Vol. 5): Sage.

Zhao, X., & Lee, T. (1993). Freezing the master production schedule for material requirements planning systems under demand uncertainty. *Journal of Operations Management, 11*(2), 185-205.

Zozom Jr, A., Hodgson, T., King, R., Weintraub, A., & Cormier, D. (2003). Integrated job release and shop-floor scheduling to minimize WIP and meet due-dates. *International Journal of Production Research, 41*(1), 31-45.