Mondragon Unibertsitatea

DOCTORAL THESIS

APPLICATION OF TOC-DBR TO MAKE-TO-ORDER MANUFACTURING SCENARIOS: SYSTEMATIC PROCESS FOR SUBORDINATION OF NON-BOTTLENECK RESOURCES TO THE BOTTLENECK

AITOR ORUE IRASUEGUI | Arrasate-Mondragón, 2023

AITOR ORUE IRASUEGUI | Application of TOC-DBR to Make-To-Order manufacturing scenarios: systematic process for subordination of non-bottleneck resources to the bottleneck

Application of TOC-DBR to Make-To-Order manufacturing scenarios: systematic process for subordination of non-bottleneck resources to the bottleneck

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A thesis submitted for the degree of

Doctoral Programme in Engineering

Department of Mechanical and Manufacturing

Mondragon Unibertsitatea

September 2023

STATEMENT OF ORIGINALITY

I confirm that the research documented in this thesis, as well as the thesis itself, was solely conducted by me at the Industrial Management Area, Mechanical and Manufacturing Department, Mondragon Unibertsitatea.

I attest that the intellectual content presented in this thesis is the result of my independent work, and I have acknowledged all sources and assistance received during its preparation.

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ACKNOWLEDGEMENTS

Bizitzako prozesu honetan nire alboan egon zareten guztioi eskerrak ematea gustatuko litzaidake. Eskerrik asko Aitor eta Unai tesi bat zer den eta nola aurrera eraman behar den erakusteagatik (disfrutatzen gainera!). Eskerrik asko lankideei "kafe bat" hartzeko denbora eskaintzeagatik. Barrea oso terapia lagungarria suertatzen da momentu konplikatuetan.

Eskerrik asko familiari ere, eskerrik asko ama, aita, Oskar, Mari,… beti hor egoteagatik.

Eta batez ere eskerrik asko bihotzez nire bizitzako proiektu pertsonalean parte hartzen duzuen hiruroi. Eskerrik asko Noa, Nahia eta Arantxa ematen didazuen guztiagatik. Zuek ez zarete kontziente zenbat laguntzen didazuen bizitza honetan.

Eta bukatzeko, zauden lekuan zaudela, eskerrik asko Santi bizitza honetan erakutsitako guztiagatik, faltan botatzen zaitugu…

LABURPENA

Gaurko enpresa industrialek konplexutasun handiagoari aurre egin behar diote, garapen teknologiko azkar, produktuen bizitza ziklo labur eta globalizazioaren eraginez. Ingurune berri eta aldakor horretan, enpresak uneoro egokitzeko gaitasuna izan behar dute, eta askok biltegiratze ekoizpeneko ingurunetik (MTS) eskaerape ekoizpeneko inguruneetara (MTO) aldatu behar izan dute.

Zenbait ikerketen arabera (Chakravorty, 2001; Darlington et al., 2015; Modi et al., 2019; Riezebos et al., 2003), mugen teoria (TOC) eta bere ekoizpenaren plangintza eta kontrol sistema (PPCS), drum-buffer-rope (DBR), MTO inguruneen arazoei erantzuteko baliozko metodologia dela frogatu dute. Hala ere, beste ikerketa batzuek (Atwater & Chakravorty, 2002; Pretorius, 2014; Wu & Yeh, 2006) zailtasunak atzeman dituzte TOC-DBR metodologia ezartzerako orduan. Arazo horietako batzuk gainditzeko Lizarraldek (2020) DBR MTO inguruneetan aplikatzeko prozesu sistematiko bat garatu du non TOC metodologiaren lehen bi urratsetan aldaketak proposatu diren. Doktorego tesi hau MTO inguruneetan TOC-DBR metodologia inplementatzeko prozesu sistematikoa osatzeko helburuarekin jaio da.

Marko teorikoan ez da TOC metodologiaren hirugarren urratsaren inplementazio sistematikoa ikertu duen artikulurik aurkitu. TOC-DBR metodologiaren berrikuspen bibliografiko sistematikoa egin ondoren, argi geratzen da bi faktorek, babes ahalmenak eta babes inbentarioak, funtsezko eginkizuna betetzen dutela sistemaren aldakortasuna xurgatzeko, metodologiaren hirugarren urratsa ezartzerakoan. Horrez gain, hirugarren urratsaren inplementazio prozesu sistematikoa diseinatzeko, prozesu taktiko eta estrategikoen alorrean berrikuspen bibliografiko espezifikoa egin da, erakundearen ikuspegi estrategikoa TOC-DBR funtzionamendu ereduan txertatzeko.

Ondorioz, ikertzaileak hiru inplementazio fase berri garatu ditu MTO inguruneetan aplikatzeko:

1) **Ereduaren konfigurazio fasea:** Definitutako urratsen bidez, kudeatzaile batek TOC-DBR metodologiaren hirugarren urratsa ezartzeko irtenbidea diseinatzen du.

2) **Eredu operatiboaren fasea:** Kudeatzaile batek urrats zehatzak jarraitzen ditu eskaeren sarrerak kontrolatzeko eta botila lepo (BN) eta bidalketa buffer denborak eta baita gaitasun bufferrak kudeatzeko. Urrats hauekin, kudeatzaileak sistema egonkor mantentzen dela ziurtatzen du zehaztutako denbora tartean.
3) **Salmenta eta operazio taktiko (S&OP) fasea:** Erakundearen plan estrategikoak exekuzio fasearekin bateratzeko urratsak definitu dira. Horretarako, eskariaren arabera lerrokaturiko negozio eredu moldagarriaren (DDAE) etengabeko hobekuntza prozesuan oinarrituta, fase operatiboaren desbideraketak aztertzen dira. Desbideratze horiek kontuan hartuta, beharrezkoa da ereduaren konfigurazio fasera itzuli eta irtenbidearen diseinua berriro aztertu eta hobekuntzak proposatzea, sistema denboran egonkor mantendu dadin eta funtzionamendu errendimendu egokia bermatu dezan.

Hiru fase hauek inplementazio prozesu sistematiko batean gehitu dira eta, horri esker, Goldratten TOC metodologiaren hirugarren urratsa praktikan jarri da. Prozesu sistematiko hau, MTO ingurune desberdinak dituzten Euskadiko bi enpresatan oinarritutako lau kasu azterketen (CS) bidez garatu da. Horretarako, tesi honek metodo misto sekuentzialaren ikuspegia erabiltzen du CS anitzen ikuspegi holistikoa erabiliz. Diseinu hau, metodo kualitatibo eta kuantitatiboak ordena sekuentzialean erabiltzen dituen ikerketa ikuspegia da.

Ikerketaren ondorioz, lau ekarpen teoriko egin dira, adibidez, MTS eta MTO inguruneetan TOC-DBR-ren hirugarren urratsa ezartzean babes ahalmenaren inpaktuaren analisia edo babes ahalmenaren definizioa faktore estrategiko bezala MTO inguruneetan jarduten duten erakundeentzat. Bestalde, TOC-DBR metodologian babes ahalmen mailaren jarraipena eta kudeaketa integratzen duten ekarpen praktiko bat ere egin da, DDAE ereduan erabiltzen den gaitasun buffer kontzeptuaren bidez.

Interesgarria da ikerketa prozesuan zehar ustekabeko beste ekarpen praktiko bat ere agertu dela. Funtsezko ekarpen praktiko honek prozesu sistematikoan fase operatiboa eta fase estrategikoa integratzeko beharrari egiten dio erreferentzia eta jarraian aurkezten da:

DDAE ereduaren bidez S&OP prozesua integratzen duten MTO inguruneetarako TOC-DBR metodologiaren hirugarren urratsaren **inplementazio-prozesu sistematikoa sortzea eta deskribatzea**. Integrazio honek bi metodologia osagarri uztartzen ditu: TOC-DBR eredua eta DDAE eredua.

RESUMEN

Las empresas industriales de hoy en día se enfrentan a una complejidad cada vez mayor debido a los rápidos avances tecnológicos, la reducción de los ciclos de vida de los productos y la globalización. En este nuevo entorno cambiante, las empresas deben ser capaces de adaptarse rápidamente, y muchas han tenido que migrar de un entorno de fabricación contra stock (MTS) a un entorno de fabricación bajo pedido (MTO).

Según algunos estudios (Chakravorty, 2001; Darlington et al., 2015; Modi et al., 2019; Riezebos et al., 2003), la teoría de las limitaciones (TOC) y su sistema de planificación y control de la producción (PPCS) tambor-búfer-cuerda (DBR), han demostrado ser una metodología válida para responder a los problemas de los entornos MTO. Sin embargo, otros estudios (Atwater & Chakravorty, 2002; Pretorius, 2014; Wu & Yeh, 2006) han detectado dificultades a la hora de implementar la metodología TOC-DBR. Para superar algunos de estos problemas, Lizarralde (2020) ha desarrollado un proceso sistemático de toma de decisiones para aplicar DBR en escenarios MTO, proponiendo cambios en los dos primeros pasos de la metodología TOC. Esta tesis doctoral nace con el objetivo de completar el proceso sistemático de implementación de la metodología TOC-DBR en entornos MTO.

En el marco teórico, no se ha encontrado ningún artículo que haya investigado la sistematización del tercer paso de la metodología TOC. Tras una revisión bibliográfica sistemática de la metodología TOC-DBR, se pone de manifiesto que dos factores, la capacidad de protección y el inventario de protección, desempeñan un papel clave en la absorción de la variabilidad del sistema a la hora de implementar el tercer paso de la metodología. Además, para diseñar el proceso de implantación sistemático del tercer paso, se ha realizado una revisión bibliográfica específica en el ámbito de los procesos tácticos y estratégicos para integrar la visión estratégica de la organización en el modelo operativo TOC-DBR.

Como resultado, el investigador ha desarrollado tres fases de implementación novedosas para aplicar en entornos MTO:

1) **Fase de configuración del modelo:** A través de los pasos definidos, un gestor diseña la solución para la implementación del tercer paso de la metodología TOC-DBR.
2) **Fase del modelo operativo:** Un gestor sigue unos pasos específicos para controlar la entrada de pedidos y gestionar tanto los búferes de tiempo del cuello de botella (BN) y de expedición, como los búferes de capacidad. Con estos pasos, el gestor garantiza que el sistema permanezca estable en el intervalo de tiempo definido.
3) **Fase táctica de ventas y operaciones (S&OP):** Se toman medidas para conciliar los planes estratégicos de la organización con la fase de ejecución. Para ello, y basándose en el proceso de mejora continua del modelo de empresa adaptable alineada a la demanda (DDAE), se analizan las desviaciones de la fase operativa. Teniendo en cuenta estas desviaciones, es necesario volver a la fase de configuración del modelo y volver a analizar el diseño de la solución y proponer mejoras para que el sistema se mantenga estable en el tiempo y garantice el rendimiento operativo.

Estas tres fases se han incluido en un proceso sistemático de implementación, que permite poner en práctica el tercer paso de la metodología TOC de Goldratt. Este proceso sistemático se ha desarrollado a través de cuatro casos de estudio (CS) basados en dos empresas del País Vasco con diferentes escenarios MTO. Para ello, esta tesis emplea un enfoque secuencial de métodos mixtos utilizando un enfoque holístico de múltiples CSs. Este diseño es un enfoque de investigación que implica el uso de métodos cualitativos y cuantitativos en orden secuencial.

Como resultado de la investigación, se han realizado cuatro contribuciones teóricas, por ejemplo, el análisis del impacto de la capacidad de protección en la implementación del paso tres de TOC-DBR en entornos MTS y MTO o la definición del nivel de capacidad de protección como factor o decisión estratégica para las organizaciones que operan en entornos MTO. Por otro lado, también se ha realizado una aportación práctica que integra el seguimiento y la gestión del nivel de capacidad de protección en la metodología TOC-DBR a través del concepto de búfer de capacidad utilizado en el modelo DDAE.

Curiosamente, a lo largo del proceso de investigación, también ha surgido otra contribución práctica inesperada. Esta contribución práctica clave se refiere a la necesidad de integrar la fase operativa con la fase estratégica en el proceso sistemático y se presenta a continuación:

Creación y descripción del proceso sistemático de implementación del tercer paso de la metodología TOC-DBR para entornos MTO **integrando el proceso S&OP a través del modelo DDAE**. Esta integración combina dos metodologías complementarias: el modelo TOC-DBR y el modelo DDAE.

ABSTRACT

Today's industrial companies are faced with increasing complexity due to rapid technological developments, shorter product life cycles and globalisation. In this new and changing environment, companies must be able to quickly adapt, and many have had to migrate from a make-to-stock (MTS) environment to a make-to-order (MTO) environment.

According to some studies (Chakravorty, 2001; Darlington et al., 2015; Modi et al., 2019; Riezebos et al., 2003), the theory of constraints (TOC) and its drum-buffer-rope (DBR) production planning and control system (PPCS) has been shown to be a valid methodology for responding to the problems of MTO environments. However, other studies (Atwater & Chakravorty, 2002; Pretorius, 2014; Wu & Yeh, 2006) have detected difficulties in implementing TOC-DBR. To overcome some of these issues, Lizarralde (2020) has developed a systematic decision-making process to apply DBR in MTO scenarios, proposing a change in the first two steps of the TOC methodology. This doctoral thesis was born with the aim of completing the systematic process of implementing the TOC-DBR methodology in MTO environments.

In the theoretical framework, no article has investigated the systematisation of the third step of the TOC methodology. After a systematic literature review of the TOC-DBR methodology, it becomes evident that two factors, protective capacity and protective inventory, play a key role in absorbing system variability when implementing the third step of the methodology. Furthermore, to design the systematic implementation process of the third step, a specific literature review has been conducted in the field of tactical and strategic processes to integrate the strategic vision of the organisation into the TOC-DBR operational model.

As a result, the researcher has developed three novel implementation phases to apply to MTO environments:

1) **Model configuration phase:** Through the designed steps, a manager designs a solution for the implementation of the third step of the TOC-DBR methodology.

2) **Operational model phase:** A manager follows specific steps to control order entry and manage both bottleneck (BN) and shipping time buffers and capacity buffers. With these steps, the manager ensures that the system remains stable in the defined time interval.
3) **Tactical Sales and Operations (S&OP) phase:** Steps are taken to reconcile the organisation's strategic plans with the execution phase. For this purpose and based on the continuous improvement process of the demand-driven adaptive enterprise (DDAE) model, the deviations of the operational phase are analysed. Taking into account these deviations, it is necessary to return to the configuration phase of the model and re-analyse the design of the solution and propose improvements to ensure that the system remains stable over time and to guarantee operational performance.

These three phases have been included in a systematic implementation process, which enables the implementation of the third step of Goldratt's TOC methodology. This systematic process has been developed through four case studies (CSs) based on two companies in the Basque Country with different MTO scenarios. For this purpose, this thesis employs a sequential mixed methods approach using a holistic, multiple-CS approach. This design is a research approach that involves the use of qualitative and quantitative methods in sequential order.

As a result of our research, four theoretical contributions have been made. For example, some of the contributions has been to analyse the impact of protective capacity on the application of step three of TOC-DBR in MTS and MTO environments or defining the level of protective capacity as a strategic factor or decision for organisations operating in MTO environments. On the other hand, a practical contribution has also been made that integrate the monitoring and management of the level of protective capacity in the TOC-DBR methodology via the concept of capacity buffer used in the DDAE model.

Interestingly, another unexpected practical contribution has also emerged throughout the research process. This key contribution relates to the need to integrate the operational phase with the strategic phase in the systematic process and is presented as follows:

Creation and description of the systematic process of implementing the third step of the TOC-DBR methodology for MTO environments **integrating the S&OP process via the DDAE model**. This integration combines two complementary methodologies: the TOC-DBR model and DDAE model.

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ABBREVIATIONS

ACRONYM	TERM
ANOVA	Analysis of variance
BN	Bottleneck
CS	Case study
DBR	Drum-buffer-rope
DDAE	Demand-driven adaptive enterprise
DDMRP	Demand-driven MRP
DDOM	Demand-driven operating model
GFS	General flow shop
GJS	General job shop
MRP	Material requirements planning
MTBF	Mean time between failures
MTO	Make to order
MTS	Make to stock
MTTR	Mean time to repair
PFS	Pure flow shop
PJS	Pure job shop
POOGI	Process of on-going improvement
PPCS	Production planning and control system
RBC	Repeat business customisers
RT	Research topics
RQ	Research question
S&OP	Sales and operations
TOC	Theory of constraints
VMC	Versatile manufacturing company
VUCA	Volatile, uncertain, complex and ambiguous
WIP	Work in progress

Chapter 1

1 Introduction

1.1 Problem outline

Today's industrial companies are faced with rapid and continuous technological development, increasing complexity of products and processes, shorter product life cycles, globalisation and high interconnectedness of the world economy (Mack & Jungen, 2016). This environment can be described as a highly volatile, uncertain, complex and ambiguous (VUCA) environment (Mack & Khare, 2016).

In this VUCA environment, consumer constraints are becoming increasingly significant in terms of a greater variety of references to be manufactured due to product customisation, fewer parts per reference, higher product quality and faster product delivery, as well as shorter product life cycles (Mack et al., 2015). Given this new and changing environment, companies must be able to quickly adapt to maintain the overall efficiency of the company and remain competitive (Affonso et al., 2008).

Due to changing customer needs, many companies have had to migrate from make-to-stock (MTS) environments to more complex customisation environments (De La Calle et al., 2017). The make-to-order (MTO) environment is particularly suited for the production of customised products (Chen-Ritzo et al., 2010).

The difference between an MTS manufacturing environment and an MTO manufacturing environment lies in whether orders are produced based on forecast demand or customer orders (Peeters & van Ooijen, 2020).

In MTS environments, production schedules are based on the forecasted demand for standard end products (Bartezzaghi & Verganti, 1995). A low variety of end products is generally offered at a lower cost. MTS systems attempt to anticipate demand to achieve customer satisfaction in a short delivery time. The main operational issues are inventory planning, lot sizing and demand forecasting. The measures focus on the product, e.g. the rate of inventory and average inventory levels (Soman et al., 2004).

One of the characteristics of MTS environments is that their system uncertainty is lower than that in MTO environments. As the degree of customisation and the number of product variants increase, the degree of uncertainty also increases (Bartezzaghi & Verganti, 1995).

MTO environments are characterised by the initiation of production or design activities after receiving customer orders. These environments are inherently dynamic, and customers may introduce changes, cancellations or additional orders during the planning horizon (S. Muda & Hendry, 2002). As a result, MTO companies cannot accurately predict demand. Consequently, they are unable to order materials and commence production in advance or effectively implement batch production methods. Moreover, the material and production requirements for each job in MTO settings may significantly differ due to the absence of common parts and varying job routes (Stevenson et al., 2005). As there is no stock of finished products, lead times are longer in MTO environments than in MTS environments. In addition, the variability of work paths increases planning and control difficulties. Consequently, production planning and control systems (PPCSs) become key elements in the management of MTO environments, as they must be able to adapt to this customization environment (Stevenson et al., 2005).

Choosing the right PPCS has recently become of great business importance worldwide and is especially important in MTO environments, as they are more unpredictable than MTS environments (Jaegler et al., 2018). Production planning and control are two key responsibilities of operational management as they have a significant impact on improving company profits as well as the efficient use of resources. As a result, PPCSs are essential for the survival of manufacturing companies in such a fiercely competitive environment (Wang et al., 2018). MTO organisations must make an important and difficult decision when selecting the right PPCSs (Gaury et al., 2001; Olhager & Rudberg, 2002; Stevenson et al., 2005)

A PPCS typically encompasses various functions, such as planning material requirements, managing demand, capacity planning and scheduling and sequencing jobs. These functions serve several key purposes, including reducing work in progress (WIP), minimising shop floor throughput times and lead times, lowering stockholding costs, improving responsiveness to changes in demand and enhancing delivery date adherence (Stevenson et al., 2005). There are different PPCSs that can be implemented in a company, such as material requirements planning (MRP), theory of constraints (TOC), workload control (WLC), Kanban, constant WIP (CONWIP) and paired cell overlapping loops of cards with authorisation (POLCA) (Stevenson et al., 2005).

Several studies have concentrated on the TOC and its application of drum-buffer-rope (DBR) PPCSs in MTO environments. According to various studies (Chakravorty, 2001; Darlington et al., 2015; Modi et al., 2019; Riezebos et al., 2003), TOC-DBR has demonstrated its effectiveness in addressing the challenges faced in MTO environments. However, certain studies have highlighted difficulties in implementing TOC-DBR (Atwater & Chakravorty, 2002; Pretorius, 2014; Wu & Yeh, 2006). Atwater and Chakravorty (2002) identified several issues, including quantifying the additional capacity of non-bottleneck (BN) resources and accurately identifying the BN, considering the temporary nature of real-world environments that may deviate from ideal conditions. Wu and Yeh (2006) explored the complexities of implementing the DBR methodology in intricate manufacturing environments, with a focus on BN re-entry flows and the sequencing of BN resources. Pretorius (2014) pointed out the deficiencies in decision-making processes that hinder smooth progression between two steps as well as the lack of clarity regarding the optimal placement of constraints.

To overcome some of these issues, Lizarralde (2020) has developed a systematic decision-making process to apply DBR in MTO scenarios, proposing a change in the first two steps of TOC methodology. This systematic process was developed and tested on four real-world cases using the action research methodology.

As the process of implementing the TOC-DBR methodology in MTO environments is unfinished, the aim of this thesis is to design a systematic process of the next step, step three (subordinating all activities to the exploitation of the BN), to complete the process. Furthermore, the systematic process is aimed at integrating different strategic factors that complement and enrich the TOC-DBR methodology.

Furthermore, it has been suggested that the level of required protective capacity is a strategic decision for the organisation (Orue et al., 2021). For managers to determine and control the necessary amount of protection and the limit of overcapacity or wasteful protection, it is essential to monitor and manage the use of protective capacity. This concept of protective capacity monitoring and control is not new to the TOC-DBR methodology, but its implementation is not as systematised as in other management models, such as the demand-driven adaptive enterprise (DDAE) model (Ptak & Smith, 2018). On the other hand, the systematic process has also been enriched by the proposed integration of the sales and operations process (S&OP) in an organisation via the TOC-DBR methodology. With this integration of the strategic part, two complementary methodologies have been united, since the TOC-DBR methodology has been employed for the operational part of the systematic process and the DDAE methodology has been utilised for the tactical, strategic part of the systematic process (Orue et al., 2023).

1.2 Research context

As mentioned in the previous section, this doctoral thesis was born with the aim of completing the systematic process of implementing the TOC-DBR methodology in MTO environments, following work by Lizarralde (2020). According to the author, a systematic decision-making process that allowed the operationalisation of the first two steps of Goldratt's DBR (the selection and exploitation of the BN) was included. This systematic process was developed and tested in four real cases and provided several theoretical contributions (e.g. how to select and exploit the BN in MTO environments) as well as practical contributions (i.e. a systematic process to operationalise the first two steps of TOC-DBR and determine how it could impact firm performance).

To develop this thesis and complete the systematic process, four case studies (CS) have been carried out based on two companies in the Basque Country with different MTO scenarios. This thesis employs a sequential mixed methods approach using a holistic, multiple-CS approach. This design is a research approach that involves using both qualitative methods and quantitative methods in sequential order to answer a research question (RQ). The purpose of using this mixed design is to gain a more complete understanding of the analysed phenomenon via quantitative research based on statistical data and techniques and qualitative research, which poses broad questions of participants and collects verbal data (Danielle et al., 2022; Johnson et al., 2007).

The sequential method is an appropriate approach for this study, as the output of one CS serves as the input for the next CS. Thus, the research process is iterative, with each CS building on the findings of the previous CS.

The methodology and research design will be described in more detail in section 3.

The first CS (a company in the Basque Country), CS1, consists of a semi-structured interview to collect qualitative data on the application of the third step of the TOC-DBR methodology. Lizarralde et al. (2019) applied the systematic process of the first two steps. The results of this study are used to design the second study, CS2, in which quantitative data are collected using a simulation. The simulation in CS2 and CS3 are based on work by Lizarralde et al (2019).

After analysing the quantitative data from CS2, assumptions are made that are used to design CS3. In CS3, manufacturing environments other than CS2 are simulated.

Based on the conclusions obtained from the quantitative data of CS3, the need arises to carry out a specific literature review as input for CS4. This specific review is based on understanding how to align the operational phase with the strategic phase.

Taking into account what was learned in CS1, CS2 and CS3 and after carrying out the specific literature review, CS4 is conducted. CS4 is based on another company in the Basque Country, where the systematic process of executing the first two steps of TOC-DBR was implemented (Lizarralde et al., 2020). In this CS4, the implementation of the third step of the TOC-DBR methodology is also analysed using semi-structured interviews. As a result of this CS4, the systematic process of the third step is obtained.

The two case companies involved in the research did not place any restrictions on the analysis, documentation, and dissemination of the research findings. The companies allowed the researchers to freely examine and report the results. However, they requested that their names remain confidential and that certain quantitative results with actual values not be disclosed. This requirement was likely established to protect sensitive or proprietary information of the case companies while still allowing the sharing of valuable insights and findings from the research.

1.3 Research questions

In the theoretical framework, no article has investigated the systematization of the subordination of non-BN resources to the BN of the TOC-DBR methodology. Furthermore, there are doubts on how and to what extent the key factors in step three affect the BN.

To answer this knowledge gap, the following RQ has been posed:

RQ1. How can non-BN resources of a production system in an MTO context be managed both systematically and by means of TOC-DBR to enhance performance?

- RQ1a. How should the level of protective capacity of non-BN resources be defined?
- RQ1b. How can the protective capacity be managed?

1.4 Research topics, contributions and related publications

1.4.1 Research topics

In this doctoral thesis, the following four main research topics (RT) are addressed:

- RT1: Complexity of MTO environments compared to MTS environments
- RT2: Impact of the protective capacity and protective inventory in MTO and MTS environments
- RT3: Capacity buffer management
- RT4: Strategic and operative key business process

1.4.2 Contributions

Considering the research gap identified after performing the systematic literature review of the third step of the TOC-DBR methodology and applying its research focus, this doctoral thesis has six key contributions:

- C1: A systematic literature review that exclusively focuses on step three of the TOC-DBR methodology is conducted. From this systematic review, the key factors affecting the subordination of non-BNs to the system are defined.
- C2: The impact and relationship of protective capacity and protective inventory on the implementation of step three of the TOC-DBR methodology in MTS environments are analysed.
- C3: The impact of protective capacity on the implementation of step three of the TOC-DBR methodology in MTS and MTO environments is analysed.
- C4: The level of protective capacity is defined as a strategic factor or decision for organisations operating in MTO environments.
- C5: The monitoring and management of the level of protective capacity in the TOC-DBR methodology is integrated by the capacity buffer concept utilised in the DDAE model.
- C6: The systematic process of implementing the third step of the TOC-DBR methodology for MTO environments is created and described by integrating the S&OP process via the DDAE model. This integration combines two complementary methodologies: the TOC-DBR model and DDAE model.

1.4.3 Research outcome: Publications, research projects and teaching

While conducting the dissertation, the researcher discovered several findings that indicated the need for an external evaluation of research quality. To conduct applied research projects on topics related to this dissertation, the researcher participated in four CSs. This gave him the opportunity to conduct and witness real-world cases. Eight Scopus/Journal Citation Reports (JCR)-ranked journals and papers presented at international conferences have published the research results and applied research initiatives. The publications (P) carried out during the doctoral thesis are listed in Table 1.

Table 1. Summary of publications

Outcome	No.	Description
Journal papers	5	(P1) Published in the **Journal of Industrial Engineering Management** (Orue et al., 2021) (P2) Published in **DYNA Management** (Orue et al., 2022) (P3) Published in **DYNA** (Orue et al., 2023) (P4) Published in **Sustainability** (Apaolaza et al., 2022) (P5) Published in the **Journal of Industrial Engineering Management** (Orue et al., 2023)
Conference proceedings	3	(P6) 14th International Conference on Industrial Engineering and Industrial Management, Leganes, 2020 (P7) 15th International Conference on Industrial Engineering and Industrial Management, Burgos, 2021 (P8) 16th International Conference on Industrial Engineering and Industrial Management, Toledo, 2022

1.4.4 Linkage of research topics, case studies, related publications and contributions

To adequately understand the content of the research, Table 2 shows the relationships among the four CSs that have been carried out, with the four RTs and the six contributions. In addition, the impact of these contributions on the eight publications is observed.

Table 2. Linkage of RTs, CSs, related publications and contributions

Main contribution	Research topic	Case study	Related publications
C1: A systematic literature review that exclusively focuses on step three of the TOC-DBR methodology is conducted. From this systematic review, the key factors affecting the subordination of non-BN to the system are defined.	**RT1 and RT2**	**CS1**	**P1 and P6**
C2: The impact and relationship of protective capacity and protective inventory on the implementation of step three of TOC-DBR in MTS environments are analysed.	**RT1 and RT2**	**CS2**	**P7**
C3: The impact of protective capacity on the implementation of step three of TOC-DBR in MTS and MTO environments is analysed.	**RT1 and RT2**	**CS1, CS3 and CS4**	**P2, P3 and P7**
C4: The level of protective capacity is defined as a strategic factor or decision for organisations operating in MTO environments.	**RT1, RT2 and RT3**	**CS1, CS3 and CS4**	**P1, P2, P3, P5, P6 and P8**
C5: The monitoring and management of the level of protective capacity in the TOC-DBR methodology is integrated by the capacity buffer concept utilised in the DDAE model.	**RT1, RT2 and RT3**	**CS3 and CS4**	**P2, P3, P5 and P8**
C6: The systematic process of implementing the third step of the TOC-DBR methodology for MTO environments is created and described by integrating the S&OP process via the DDAE model. This integration combines two complementary methodologies: the TOC-DBR model and DDAE model.	**RT1, RT2, RT3 and RT4**	**CS1 and CS4**	**P1, P4, P5, P6 and P8**

Figure 1 summarises the research programme and the main tasks of the doctoral thesis. These tasks include the literature review, the development and evaluation of the systematic process of implementing the third step of the TOC-DBR methodology, and as the quality standards applied to validate the research.

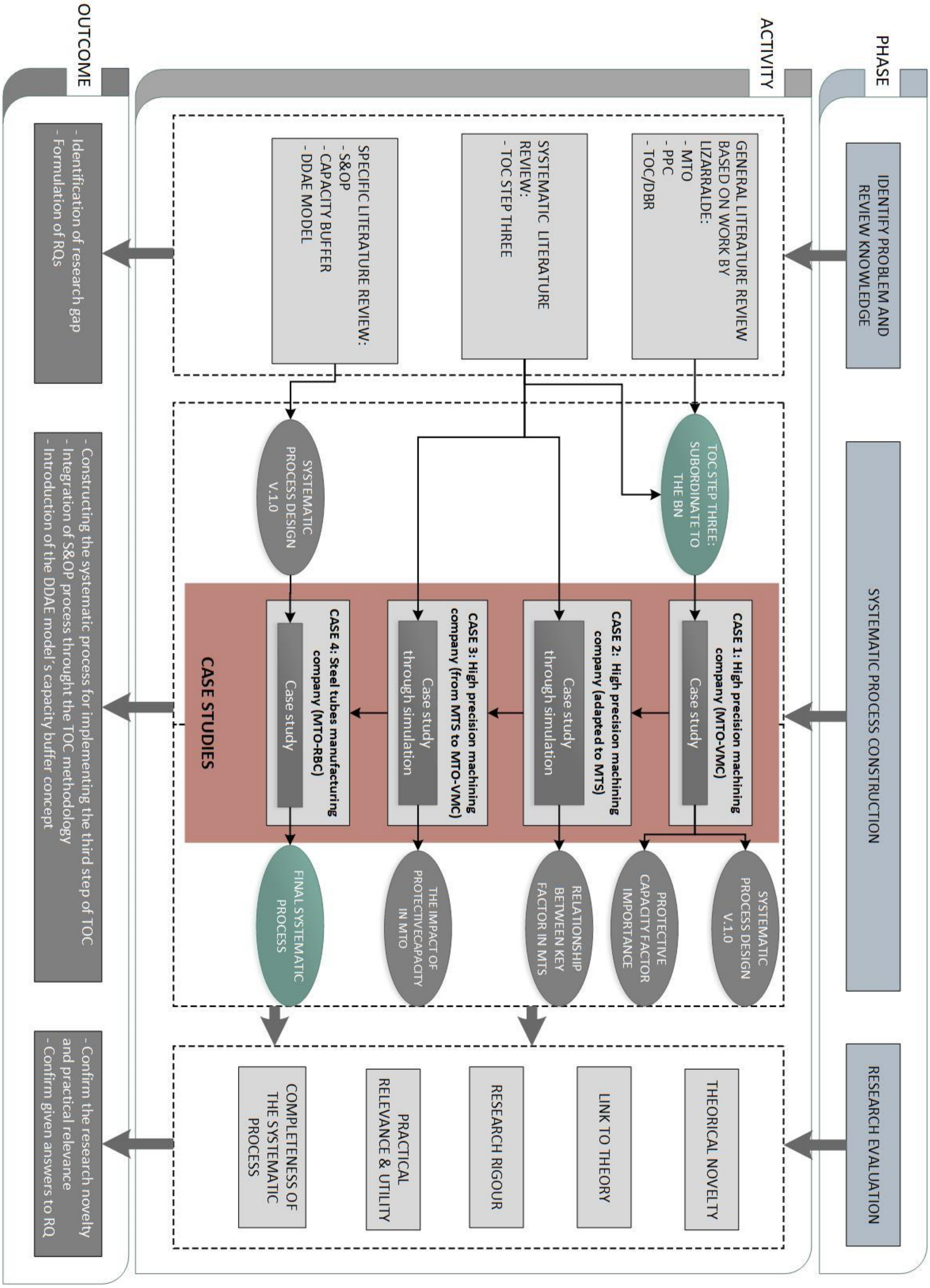

Figure 1. Research programme

1.5 Structure of the document

Table 3 summarises the seven chapters that comprise this thesis.

Table 3. Chapter descriptions

Chapter	Description
Chapter 1: Introduction	The research project is described, and the study's objectives and purpose are examined.
Chapter 2: Literature review	The main factors involved in the implementation of the third step of the TOC-DBR methodology are identified.
Chapter 3: Research methodology and design	To choose the approach that will be employed for this research, various research methodologies are analysed.
Chapter 4: Fieldwork	Four CSs are reported, and the results and managerial implications are explained.
Chapter 5: Discussion	The main findings of the CSs are utilised to answer the RQs.
Chapter 6: Conclusions and future research	The conclusions are presented, and future research directions are identified.
Chapter 7: References	The references are listed.

Chapter 2

2 Literature review

2.1 Introduction

The aim of this chapter is to analyse and describe the theoretical framework in which this thesis will be developed. The starting point is the work carried out by Lizarralde (2020) regarding the systematisation of the implementation process of the first two steps of the TOC-DBR methodology in MTO environments. Lizarralde (2020) has commented about the future research lines of his doctoral thesis:

> 'This research is limited to the first two steps of the Process of On-Going Improvement (POOGI). Extending the findings by providing new research on the third step of POOGI would have high value, as the first three steps are key for maximising the performance of the current system. More insights on subordinating the remainder of a company's resources to the BN programme are needed to enrich the theory-building concerning PPCS for MTO contexts.'

It is clear that to be able to continue with the initiated research, an analysis of the existing literature must be carried out with regard to the following relevant aspects:

- Characteristics of companies with MTO environments
- TOC methodology in MTO environments
- Systematic literature review of the third step of the TOC
- Research gaps

2.2 Characteristics of companies with make to order environments

The characteristics of manufacturing environments differ depending on whether manufacturing is based on forecasted demand or directly on incoming orders from customers. In the literature, the first manufacturing environment is referred to as MTS and the second manufacturing environment is referred to as MTO (Peeters & van Ooijen, 2020).

In MTO manufacturing environments, product design or manufacture begins when a customer order is received. Because the customer can change, cancel or add orders during the planning horizon, they are dynamic and changeable environments by nature (S. Muda & Hendry, 2002). Consequently, companies working in MTO environments cannot accurately predict demand. For this reason, these companies also cannot order materials and produce in advance or effectively implement batch production methods. In addition, the material and the production requirements of a job can be very different from those of other jobs due to a lack of common parts and variable work routes (Stevenson et al., 2005).

To define the characteristics of MTO companies, Amaro et al. (1999) presented a new classification of “non-MTS” companies based on the level of work carried out after the order has been placed and the nature of customization. In the case of an MTO company, when an order is placed, a basic design is already available and the remaining work is concerned with manufacturing and assembly.

Amaro et al. (1999) classifies MTO companies into two types: Repeat Business Customisers (RBC) and Versatile Manufacturing Companies (VMC). For RBC, the products are customised but can be produced more than once, which allows a small degree of predictability. Otherwise, the VMC market is more complicated because the order is individually made with a wide variety of products and variable demand is manufactured in small batches with minimal repetition. Although both RBC and VMC allow customisation, RBC is more stable and ensures more stability by enticing customers into a more predictable and committed relationship. Figure 2 illustrates the positions of the RBC and VMC categories in relation to the MTS category.

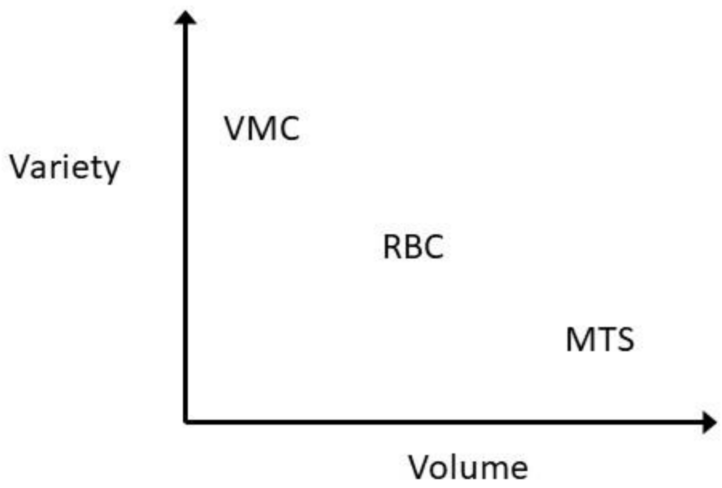

Figure 2. Classification volume versus variety. Note: based on Stevenson et al. (2005)

The workshop configuration is another key feature in MTO environments. There are different types of workshop configurations, such as the pure flow shop (PFS), the general flow shop (GFS), the general job shop (GJS) and the pure job shop (PJS). The key difference between the job shop and the flow shop is the direction of material flow. In the PFS, work travels in one direction through a sequence of work centres in strict order, which is unlikely in an MTO company. In the GFS, work still travels in one direction but jobs are allowed to visit a subset of work centres, permitting limited customisation, relevant to an RBC. PJS routing sequences are random; jobs can start and finish at any work centre allowing complete freedom and customisation (Stevenson et al., 2005). Note that the job shop is still an appropriate configuration for many MTO Companies (Muda & Hendry, 2003). The GJS is defined as providing for multi-directional routing but with a dominant flow direction, which is relevant to both VMC groups and RBC groups (Stevenson et al., 2005). Figure 3 attempts to present a PPC system selection matrix that summarises what Stevenson et al. (2005) consider to be the most applicable PPC options for companies in the MTO sector.

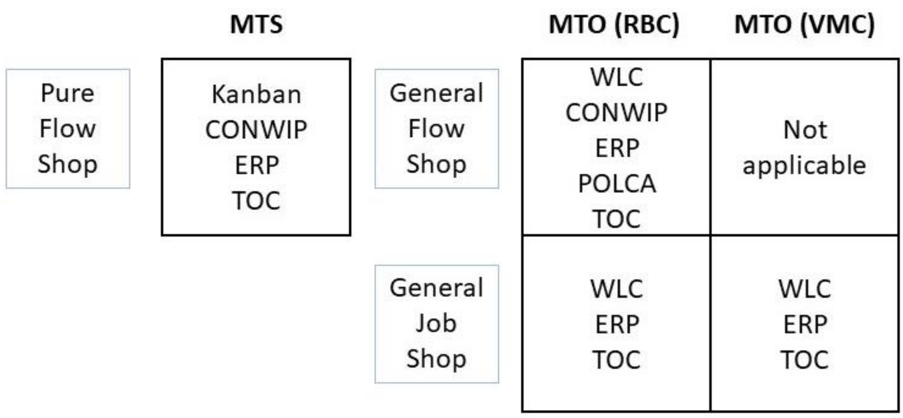

Figure 3. System selection matrix presenting PPC alternatives for the MTO sector. Note: based on Stevenson et al. (2005)

Consequently, authors such as Jaegler et al. (2018) point out that PPCS have become key elements in managing the flow of materials in production plants. Moreover, these PPCS must be able to adapt to the customisation of MTO environments (Stevenson et al., 2005).

The TOC-DBR methodology has proven to be a valid methodology to respond to the challenges of MTO environments (Chakravorty, 2001; Darlington et al., 2015; Modi et al., 2019; Riezebos et al., 2003). Therefore, to deepen the TOC-DBR methodology in MTO environments, the following section will review existing literature.

2.3 Theory of constraints methodology in make to order environments

The TOC methodology is a holistic management philosophy developed by Dr. Eliyahu M. Goldratt, based on the principle that complex systems exhibit inherent simplicity. Even a highly complex system composed of thousands of people and pieces of equipment may, at any given time, have only a minute number of variables or even just one variable known as the constraint, that truly limit the system's capacity to generate more units of objectives (Cox et al., 2012). This management methodology is based on systemic thinking (Boyd & Gupta, 2004) and revolves around the fundamental concept that every system has at least one constraint. These constraints serve as the foundation for managing and improving a system (Goldratt & Cox, 2004).

To properly understand the TOC methodology and its implications, it is important to understand what a constraint is. Cox et al. (2012, p. 28), who are editors of the Theory of Constraints International Certification Organization (TOCICO) Dictionary, define constraint as:

> ‘The factor that ultimately limits the performance of a system or organisation. The factor that, if the organisation were able to increase it, is more fully exploited or more effectively subordinate to it, would result in achieving more of the goal.’

The concept of a constraint should not be confused with a ‘resource BN’, which is defined as

> ‘Any resource whose capacity is less than or equal to the demand placed on it for the specified time horizon (Cox et al., 2012, p. 9).’

For simplicity's sake, the concepts of constraint and BN will be used interchangeably throughout the thesis report.

The five steps of the TOC methodology are listed as follows (Goldratt & Cox, 2004): (1) identify the constraint of the system, (2) decide how to exploit this constraint, (3) subordinate everything else to the constraint, (4) elevate the system´s constraint and (5) if in any of the previous steps the constraint is broken, return to step one.

The TOC scheduling mechanism, DBR (Figure 4), is a PPCS in shops with BNs, and addresses both market constraints and physical constraints (Thürer et al., 2017). DBR is a simple approach to managing the whole system, and only precision is required at the BN (drum) (Gupta & Snyder, 2009). When the BN is identified or selected, DBR synchronises manufacturing with the customer requirements via the rope. This rope connects the incoming manufacturing requirement with the BN (Thürer et al., 2017). The scheduling of the BN is performed based on the company's sales, and the programme criteria is previously defined in step two, system exploitation. DBR uses BN buffer and shipping buffer (time or amount of time equivalent to WIP) to enable synchronisation while protecting system performance from variability with low WIP levels (Thürer et al., 2017). Generally, non-BN resources are not scheduled as each operation is governed by buffer consumption (Goldratt & Cox, 2004).

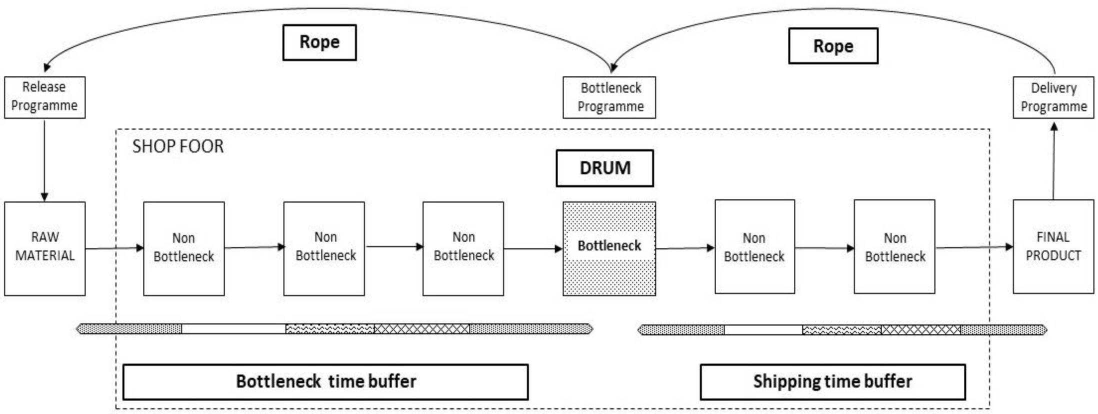

Figure 4. DBR scheduling mechanism

Multiple studies have validated the effectiveness of the TOC-DBR methodology in MTO environments by demonstrating its positive impact on workflow performance. These studies have shown that implementing TOC-DBR in MTO settings leads to reduced lead times, decreased cycle times and increased revenue (Chakravorty, 2001; Darlington et al., 2015; Modi et al., 2019; Riezebos et al., 2003).

However, alternative studies have highlighted the challenges encountered when implementing the TOC-DBR methodology in dynamic environments. Atwater and Chakravorty (2002) outlined various issues, such as the difficulty in quantifying the additional capacity of non-BN resources and accurately identifying the BN. The authors emphasised that real-world environments often represent temporary situations that may deviate from ideal conditions. In a different vein, Wu and Yeh (2006) examined the intricacies of implementing the DBR methodology in complex manufacturing settings, with a focus on BN re-entry flows and the sequencing of BN resources. Additionally, Pretorius (2014) identified limitations in decision-making processes that hinder smooth progression from one step to the next step, with a lack of clarity regarding the optimal placement of constraints.

Several researchers have addressed the challenges discussed earlier by proposing alternative approaches. Pretorius (2014) introduced a decision map that encompassed all five steps of the TOC methodology. This map outlined strategic checkpoints that assist companies in making informed decisions and transitioning smoothly from one step to another step. On the other hand, Lizarralde (2020) presented a strategic perspective for the selection and exploitation of BN resources. The researcher developed a systematic decision-making process that streamlined the first two stages of DBR. As shown in Figure 5, the researcher provided four criteria to guide the selection of BNs.

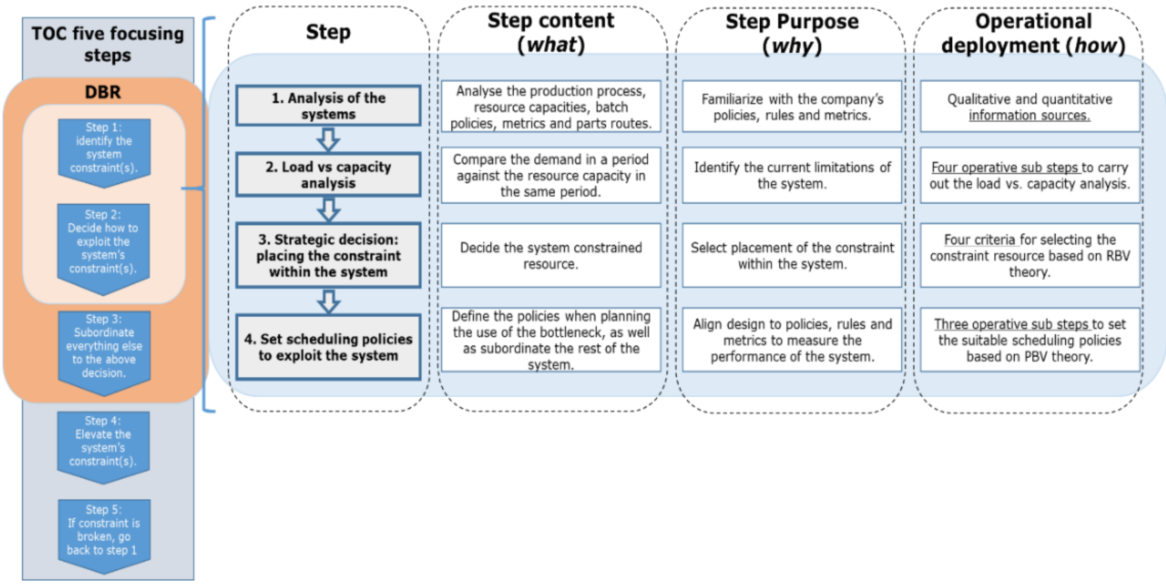

Figure 5. Systematic implementation process for TOC steps one and two (Lizarralde et al., 2020, p. 25)

As shown in Figure 6, sub-steps on how to operationally deploy Steps two, three and four were also included.

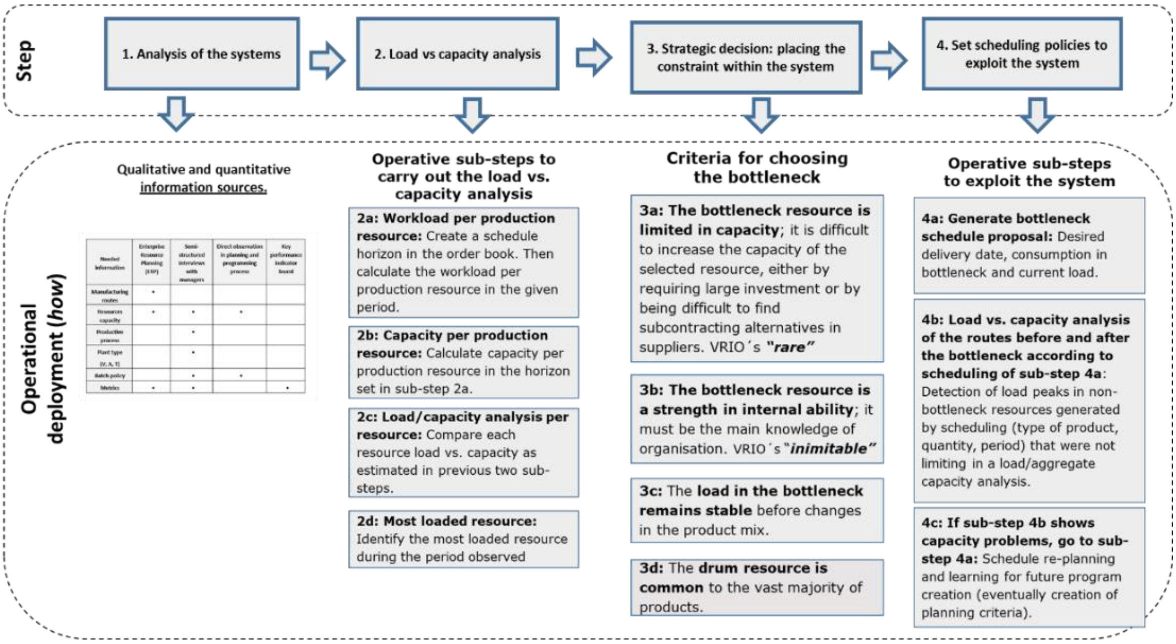

Figure 6. Systematic process steps, including operational deployment sub-steps (Lizarralde, 2020, p. 119)

To continue developing the systematic process, it is necessary to add the third step of the TOC-DBR methodology. This requires carrying out a systematic review of specific literature.

2.4 Theory of constraints third step systematic literature review

In the third step of the TOC methodology, the focus is managing the resources that are not considered constraints, requiring them to operate in a manner that supports the constraint. Non-BN resources inherently possess more capacity than constraints, which means that performing work beyond what is necessary will only result in WIP that the constraint cannot handle. Step three involves managing non-BN resources and their level of utilisation, which is determined by the capacity and utilisation of the constraint, rather than the potential capacity of the non-constraint resources (Goldratt & Cox, 2004).

To gain a deeper understanding of the third step of the TOC, a systematic review of the existing literature is conducted. A systematic literature review involves a rigorous assessment and identification of relevant research pertaining to a specific RQ, topic area or phenomenon of interest (Kitchenham, 2004). To ensure a comprehensive review, it is essential to establish a well-defined research strategy (Kitchenham, 2004). The literature review in question follows a strategy based on the framework proposed by Kitchenham (2004), with detailed information provided in Figure 7.

Figure 7. Systematic literature review methodology. Note: based on Kitchenham (2004).

2.4.1 Planning the review

The motivation behind this research stems from the potential to enhance the systematic implementation of the TOC-DBR methodology, particularly building upon Lizarralde's (2020) systematisation of the first two steps. The objective of this literature review is to examine the existing body of research on the implementation process of the third step of TOC-DBR in MTO environments. Specifically, the focus is identifying the key factors involved in subordinating the system to the BN resource.

When planning a literature review, it is essential to establish a protocol that outlines the methodology to be applied for conducting a systematic review. This protocol is necessary to minimise researchers' bias (Kitchenham, 2004).

The defined protocol is presented as follows:

2.4.1.1 Keywords to carry out the literature review

The articles under consideration specifically concentrate on the third step of the TOC, which involves the subordination of all elements to the BN. To select the keywords, a selection process has been utilised to ensure that the search is exhaustive and efficient. The process includes the following steps:

- A general literature review of the TOC-DBR methodology is conducted, and key words and aspects that have a bearing on the implementation of the third step are defined.
- A pilot search is conducted using the initial set of keywords to test the feasibility of the search strategy. This approach can help to identify potential problems or areas where the search needs to be refined.
- The search results are reviewed, and additional keywords or related terms that frequently appear in the literature are identified.
- The keyword list is refined based on the search results, and the search strategy is adjusted as necessary.

Once the process was applied, all keywords and their combinations were entered into the search engines for title, abstract and keywords. All the combinations are presented below:

- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘make to order’ OR ‘MTO’
- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘subordination’
- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘workload’
- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘variability’

- 'Drum buffer rope' OR 'DBR' OR 'theory of constraints' OR 'TOC' AND 'step three'
- 'Drum buffer rope' OR 'DBR' OR 'theory of constraints' OR 'TOC' AND 'problematic'
- 'Drum buffer rope' OR 'DBR' OR 'theory of constraints' OR 'TOC' AND 'implementation' AND 'variability'
- 'Drum buffer rope' OR 'DBR' OR 'theory of constraints' OR 'TOC' AND 'protective inventory' OR 'protective capacity'
- 'Drum buffer rope' OR 'DBR' OR 'theory of constraints' OR 'TOC' AND 'capacity buffer'
- 'Drum buffer rope' OR 'DBR' OR 'theory of constraints' OR 'TOC' AND 'starvation'
- 'Bottleneck' AND 'protective capacity'
- 'Bottleneck' AND 'protective inventory'
- 'Bottleneck' AND 'capacity buffer'

2.4.1.2 Sources to identify primary studies

The research utilised the Scopus and Web of Science databases, which are renowned for their extensive collections of citations and abstracts from peer-reviewed literature. The databases encompass a wide range of publications from prominent operations and management publishers that are included in their indexes. Furthermore, Google Scholar was explored as an additional resource to identify potential articles.

2.4.1.3 Selection of the exclusion and inclusion criteria for the studies

The articles were selected, analysed and evaluated based on the following criteria: (1) a primary emphasis on the third step of the TOC; (2) publication in an academic journal or conference proceedings; (3) inclusion of case studies, encompassing both simulated scenarios and real-world scenarios; (4) exclusion of articles that incorporated any other methodology alongside TOC-DBR; and (5) exclusion of articles intended for final bachelor's or master's degree submissions.

2.4.1.4 Period of publication

The delimited publication period was from 1990 to 2022. The TOC-DBR methodology is a well-established methodology that has been applied to a wide range of industries and business situations since its development in the early 1980s. The first major studies on the TOC-DBR methodology, including academic research articles, CSs and books, began in the early 1990s. To conduct a comprehensive and rigorous systematic literature review of this literature, it is necessary to include studies that have been published throughout this period (from 1990 to 2022). 2022 was selected as the end date of the publications to maximise the number of studies with as many updates as possible.

2.4.1.5 Study quality assessment

For this research, both quantitative documents and qualitative documents were taken into account. The evaluation of the selected journals' quality was based on indicators such as the Journal Citation Report and SCImago Journal Rank.

2.5 Conducting the review

A search strategy was devised with the aim of conducting an unbiased search to identify as many primary studies as possible that are relevant to the implementation process of the third step of the TOC methodology.

Since few studies directly reference the implementation of this step, the initial decision was made to select terms such as 'theory of constraints' or 'TOC', 'drum buffer rope' or 'DBR' and 'bottleneck'. These keywords were chosen to ensure that the articles primarily focused on TOC-DBR. To further refine the search and narrow the focus on the implementation of the third step of the TOC, additional key terminologies related to the subordination of the system to the BN resource were included. Figure 8 illustrates the selection process that was conducted.

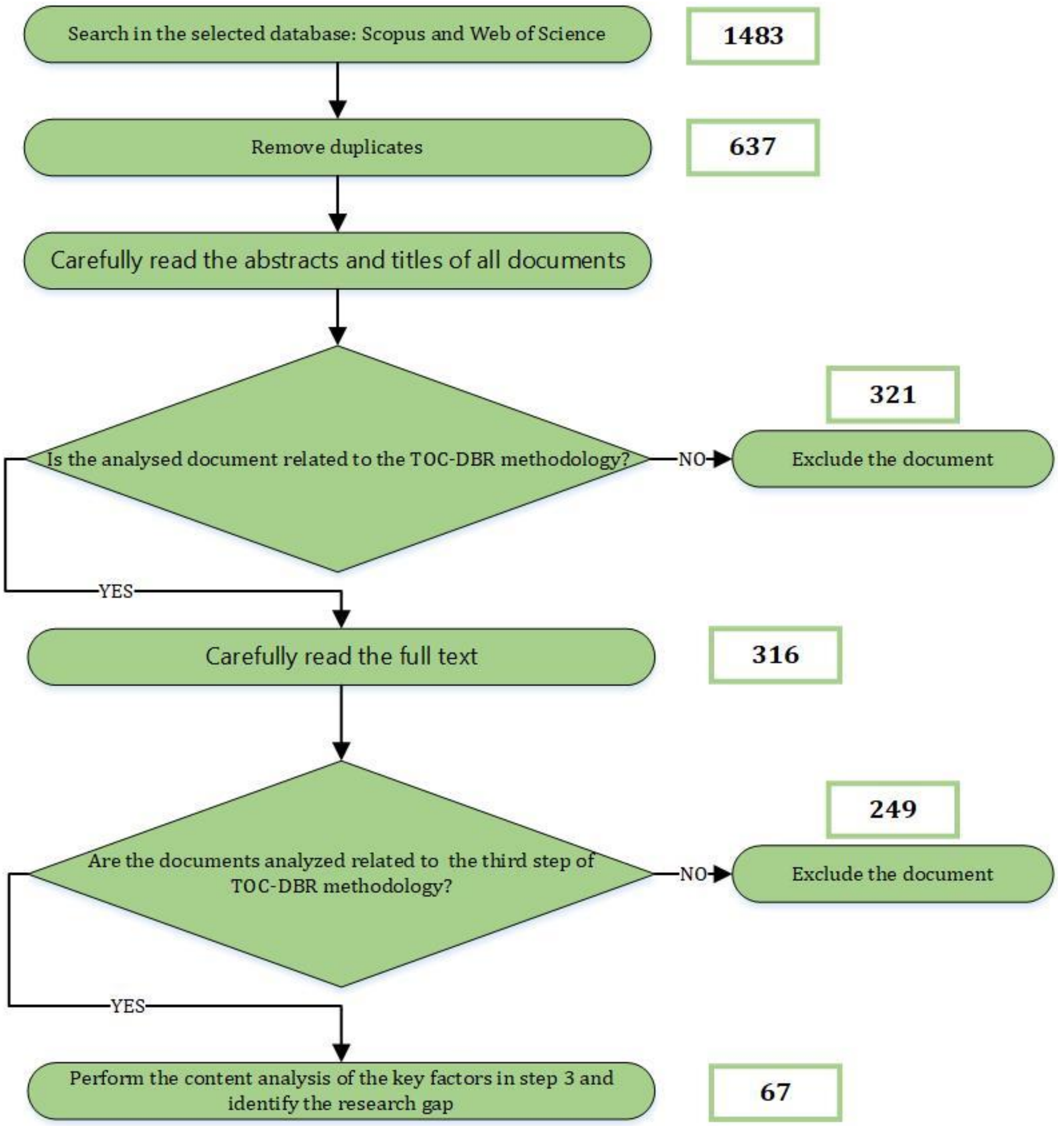

Figure 8. Literature review selection process.

Following this process, 67 articles remained, which were carefully reread. Figure 9 and Figure 10 show the 67 analysed articles by publication year and journal of publication, respectively.

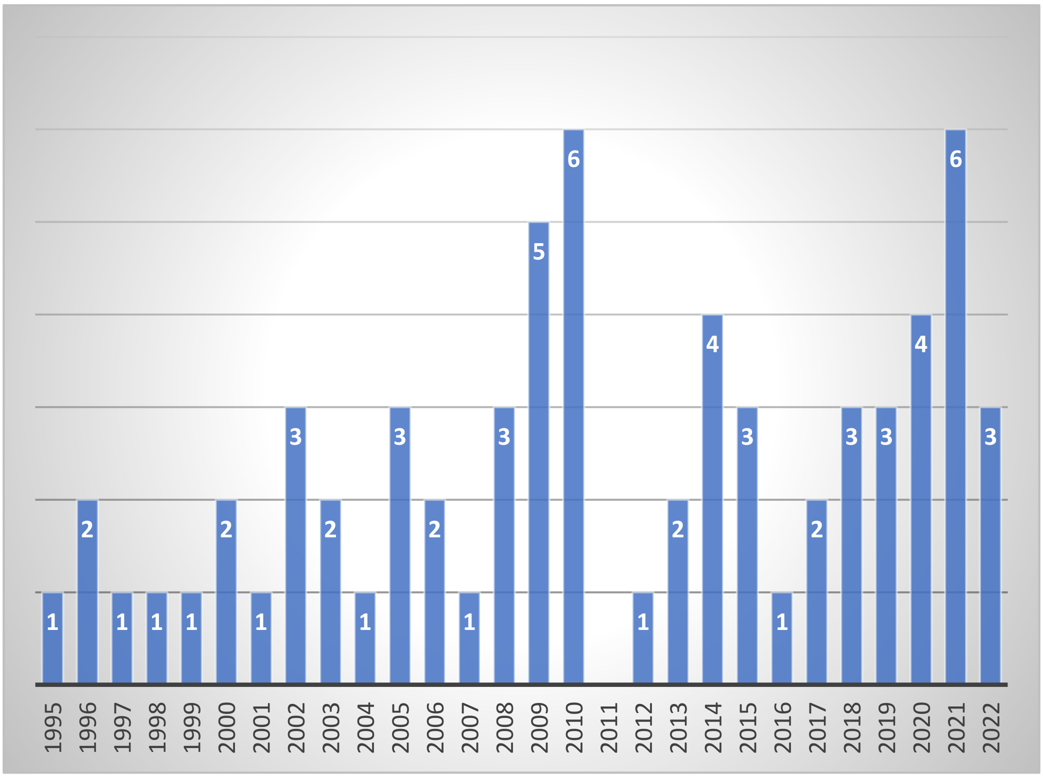

Figure 9. Frequency of TOC-DBR selected papers, 1990–2022.

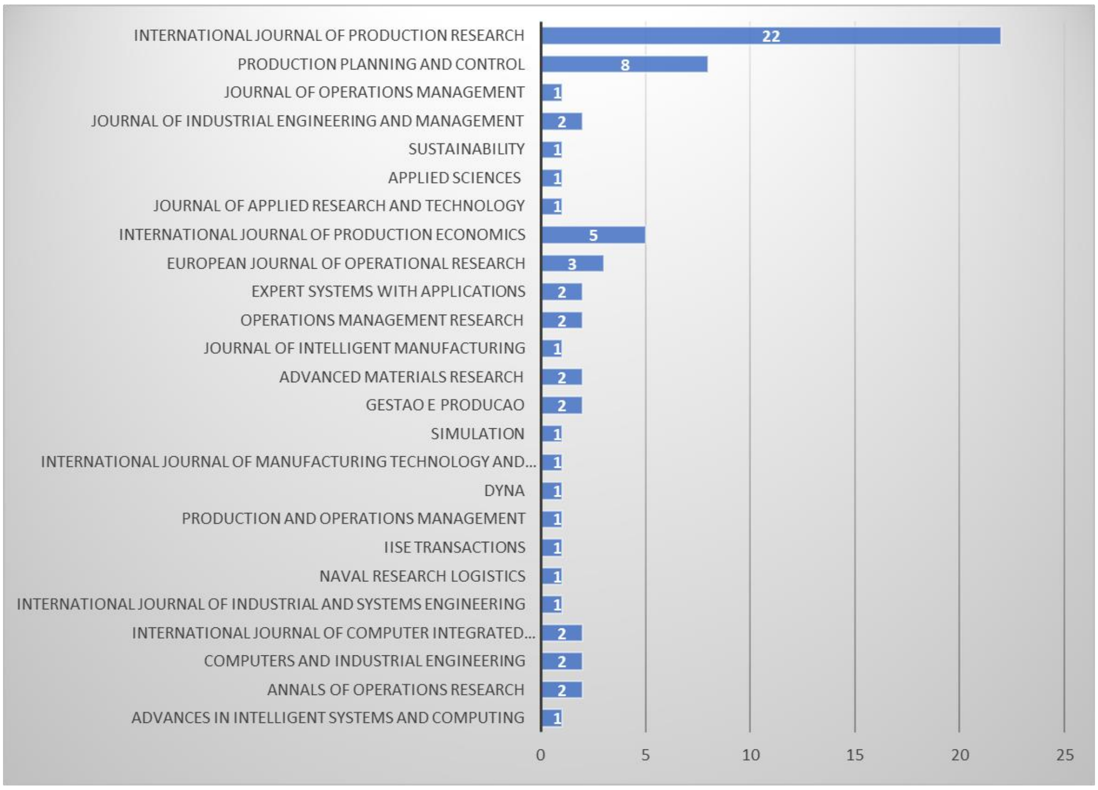

Figure 10. TOC-DBR selected articles in journals by publisher.

2.6 Document review

As explained in Section 2.4, Step three of the TOC methodology focuses on non-constraint resources, which need to operate in a manner that supports the constraint. It is crucial to safeguard the constraint from variations and uncertainties within the system to ensure that the planned throughput is not hindered (Patterson et al., 2002).

Variability within the system can lead to a situation in which non-constraint resources fail to provide work to the constraint, despite the constraint being available to work. This condition, known as constraint starvation, occurs when the WIP does not arrive on time at the constrained workstation (Blackstone & Cox, 2002). To mitigate constraint starvation, two different methods are commonly employed in practice. The first method involves utilising the capacity margin in non-constraint resources, which is often referred to as protective capacity. The second method involves maintaining a WIP inventory in front of the BN resource, which is known as protective inventory (Blackstone & Cox, 2002; Kim et al., 2010).

The two methods and their implications identified in the systematic literature review are described in the next section.

2.6.1 Protective capacity

To comprehend the concept of protective capacity, it is crucial to grasp some fundamental terms. As depicted in Figure 11, capacity can be categorised into two main types: productive capacity and idle capacity.

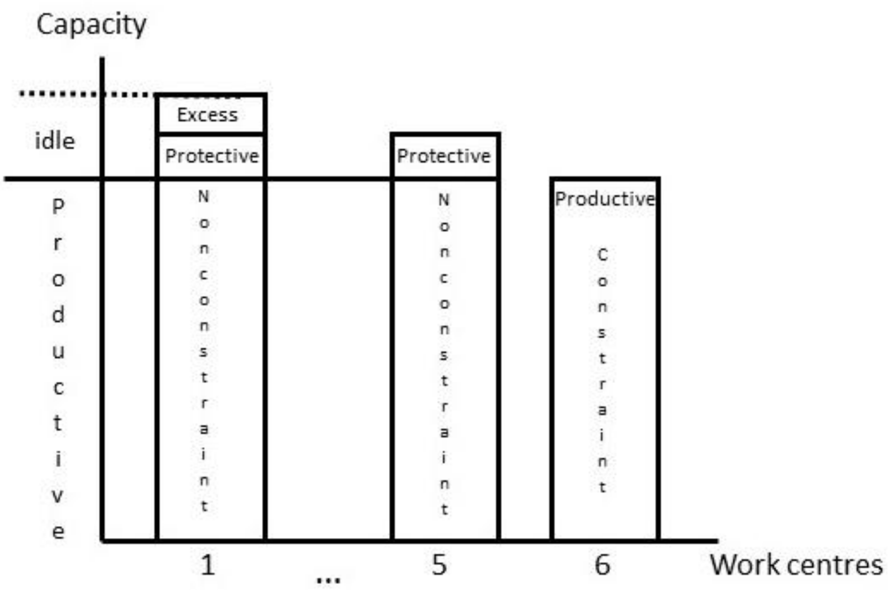

Figure 11. Productive and idle (protective and excess) capacities. Note: based on Kim et al. (2010)

Productive capacity is defined as 'the maximum of the output capabilities of a resource (or series of resources)' (Pittman & Atwater, 2016, p. 146).

Idle capacity is defined as 'the available capacity that exists on the non-constraint required to support the constraint. Idle capacity has two components, protective capacity and excess capacity' (Pittman & Atwater, 2016, p. 83).

Protective capacity is defined as the 'resource capacity needed to protect the throughput of the system by ensuring that some capacity above the capacity required to exploit the constraint is available to catch up when disruptions inevitably occur' (Pittman & Atwater, 2016, p. 149). Blackstone and Cox (2002, p. 419) defined protective capacity as 'the capacity needed at non constraint work stations to restore WIP inventory to the location adjacent to and upstream of the constraint work station to support full utilisation of the constraint work station'.

The findings from the literature review indicate that protective capacity plays a crucial role in the performance of a system. Atwater and Chakravorty (1994) highlighted that the utilisation of protective capacity is a significant factor in achieving faster cycle times and operating with lower inventory levels. Caridi et al. (2006) emphasised the relevance of protective capacity in determining productivity. Atwater and Chakravorty (2002) demonstrated that the inclusion of protective capacity at the second most heavily utilised station can enhance system performance. Craighead et al. (2001) supported earlier studies by confirming that the strategic placement of protective capacity can reduce mean flow time. Lawrence and Buss (1994) reported that higher levels of protective capacity decreased BN shiftiness at all BN utilisation levels.

The reviewed studies unanimously acknowledge the necessity of protective capacity in non-BN resources. However, as stated by Tu et al. (2005), determining the appropriate amount of protective capacity is challenging. Patti, Watson, and Blackstone (2008) focused their research on examining the quantity of protective capacity required to achieve improvements in production and distribution as well as the configuration of that protective capacity in production systems. Craighead et al. (2001) conducted a comprehensive investigation of the impact of protective capacity on system performance. As outlined in the future directions suggested by Caridi et al. (2006), protective capacity is considered a viable means of achieving faster cycle times and reducing inventory. Nevertheless, it is important to recognise that this additional capacity incurs associated costs.

2.6.2 Protective inventory

To comprehend the concept of protective inventory, we employ a logical approach similar to that of protective capacity. The concept of protective inventory shares implications and definitions similar to that of protective capacity (Blackstone & Cox, 2002).

Productive inventory is defined as the quantity of WIP inventory, measured in units of time, that is necessary to support the constraint until the material can flow from the initial operation to the constraint (Blackstone & Cox, 2002).

‘From a theory of constraints perspective, idle inventory generally consists of protective inventory and excess inventory’ (Pittman & Atwater, 2016, p. 83).

Protective inventory is defined as 'the amount of inventory required relative to the protective capacity in the system to achieve a specific throughput rate at the constraint' (Pittman & Atwater, 2016, p. 149).

Protective inventory shares considerations similar to that of protective capacity, as highlighted in various studies. The need for protective inventory to safeguard throughput from variability is emphasised. Blackstone and Cox (2002) discuss the concept of using a certain amount of protective WIP to mitigate the impact of statistical fluctuations at non-constraint work stations on the constraint work station and overall system throughput. Betterton and Cox (2009, p. 68) indicated that 'for real lines, protective inventory at any point in time is inventory upstream of the constraint over and above the deterministic productive number of units. Protective inventory is WIP inventory that the constraint needs for uninterrupted operation in a non-deterministic system'.

Various formulas have been developed to calculate the productive inventory required in a system to maximise throughput. Schragenheim and Ronen (1990) outlined a process for establishing these buffers, which involves dividing the company's current lead-time allowance in half. One portion is designated as the constraint buffer, while the other portion serves as the shipping buffer. By utilising this approach, managers can determine initial buffer sizes and refine them over time until optimal buffer sizes are identified.

Contrary to the existence of a mathematical approach for determining protective inventory (or protective capacity), Blackstone and Cox (2002) assert that defining the "adequate" level of protective inventory is a challenging task. While it is essential to have a sufficient level of protection to mitigate the impact of statistical fluctuations in the system, the difficulty lies in precisely defining what constitutes an "adequate" level of protective inventory (Blackstone & Cox, 2002). As excess inventory poses risks such as increased WIP and extended production lead times, it becomes crucial to identify the minimum levels of protective inventory (Khalil et al., 2008).

2.7 Research gaps

After conducting a comprehensive systematic literature review of the third step of the TOC-DBR methodology, it is evident that significant research efforts have been devoted to understanding various factors that influence step three. However, despite the existing research, a series of research gaps have been identified, which are presented below.

A thorough analysis of the articles reveals that most of the research is based on computer simulations. Of the research articles that analyse results of implemented cases, 89% are simulations in companies and only 11% are real cases in companies.

The attainment of more CSs based on real-world implementations in industrial companies in MTO environments would be valuable for validating the results obtained via simulation.

GAP 1: Lack of empirical case studies based on real implementations in industrial companies in MTO environments.

Based on a comprehensive analysis of the literature review, it is evident that the levels of protective capacity and protective inventory have significant impacts on mitigating variability in a system. These levels of protection directly influence the cycle time and throughput of the system.

However, as emphasised by Blackstone and Cox (2002) in their conclusions, there is no definitive mathematical approach for precisely defining the optimal levels of protective inventory and protective capacity.

GAP 2: Lack of a criterion to define and manage the protective capacity and protective inventory when implementing the third step of the TOC-DBR methodology in MTO environments.

When it comes to deciding whether to use protective capacity or protective inventory to address system variability, there is a dilemma in this choice (Figure 12). If the utilisation of protective capacity is chosen for the non-BN resource, the resource will not be saturated, which results in low efficiency in terms of return on investment. On the other hand, if protective inventory is selected as a factor to absorb variability, it increases the WIP of the system, resulting in longer lead times.

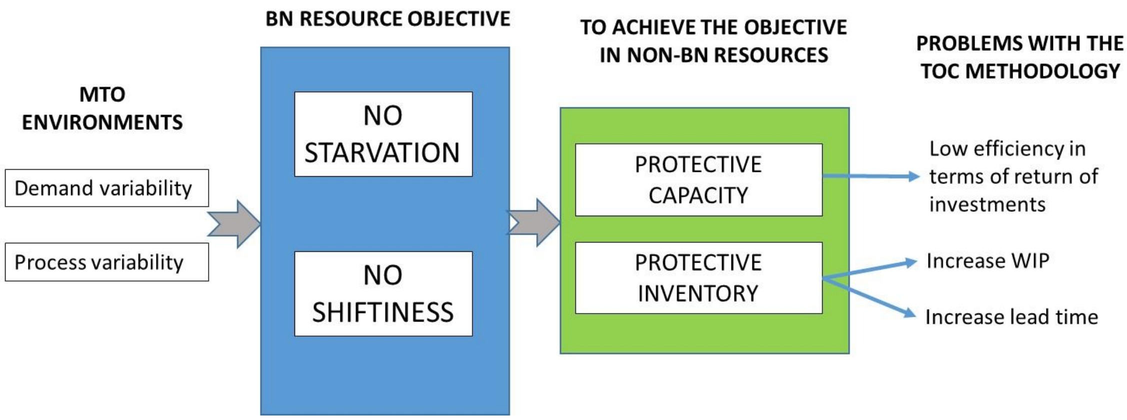

Figure 12. Differences between protective capacity and protective inventory.

The literature review revealed that no research studies have analysed the relationship between protective capacity and protective inventory in different manufacturing environments.

GAP 3: Lack of research studies analysing the relationship between protective capacity and protective inventory in MTS and MTO environments.

Regarding the theoretical framework, no article has investigated the systematisation of the third step of the TOC methodology. As Pretorius (2014) mentions, there is a lack of clarity regarding the decisions that allow moving to the next step or previous step in the TOC-DBR methodology. In addition, all the information about the third step of the methodology that has been extracted using key factors are concerned with the subordination of the system to the BN.

GAP 4: Lack of a systematic process for implementing the third step of the TOC-DBR methodology for MTO environments.

Considering the conclusions of the literature review in step three, it can be seen that there is no systematic procedure for determining the “adequate” level of protective capacity or protective inventory. Faced with the dilemma of "choosing" to increase protective capacity with its consequence of low efficiency in terms of return on investment or increasing protective inventory with its consequence of increased WIP and lead time, the solution remains ambiguous. To help make a strategic decision, a systematic decision-making process should be designed.

In conclusion, there is a distinct need for research on the systematisation of the third step of the TOC methodology in MTO environments.

Chapter 3

3 Research methodology and design

The development of an investigation is a structured goal-oriented process, to which the selected method must be adjusted (Reichart & Holweg, 2006). Therefore, it is essential to precisely define the research methodology to correctly establish an appropriate path in terms of effectiveness, which implies the creation of the process itself (Robson & McCartan, 2016; Yin, 2018).

This chapter will address the most relevant aspects of the research methodology employed during the research project. The research objectives and RQs (Section 3.1), research methodology and design concepts (Sections 3.2 and 3.3), selected research strategy (Section 3.4), research tactics (Section 3.5) and the research programme of this thesis are detailed (Section 3.6).

To successfully conduct a research, it is necessary to understand the difference between research methodology and research design. Research methodology refers to the overall approach or strategy applied to conduct research, including the methods, techniques and procedures used to collect and analyse data (Kazdin, 2016). Research design, on the other hand, refers to the various possible ways of conducting a study to answer the RQ (Marczyk et al., 2010). It is important to carefully consider both the methodology and the research design to ensure that the research is rigorous and well organised. The research methodology will guide the overall approach to the research, including the types of data that will be collected and the methods that will be utilised to analyse the data. The selection of a solid research methodology will help ensure that the research is conducted in a systematic and meaningful way and that the findings are valid and reliable.

3.1 Research objectives and questions

As mentioned in section 2.1. Introduction, this doctoral thesis was born with the aim of completing the systematic process of implementing the TOC-DBR methodology in MTO environments, following work by Lizarralde (2020). The aim is to add the third step of the TOC-DBR methodology to the systematic process.

The specific literature review shows a lack of empirical CSs, as only 11% of the articles analysed in detail are real cases in companies.

For this reason, **the first objective** of this research work is **to provide empirical CSs on the implementation of the TOC-DBR methodology in MTO environments.**

Additionally, in the theoretical framework, no work has investigated the systematisation of the subordination of non-BN resources to the BN.

Different authors point out several aspects that should be answered in future research in relation to the third step. Pretorius (2014) points out that in the TOC, there is a need for improved decision-making to facilitate the transition from one step to the next step.

On the other hand, Lizarralde (2020), regarding the future direction of the doctoral thesis, adds that it would be valuable to extend the results by providing new research on the third step of POOGI, as the first three steps are the key to maximising the performance of the current system.

Taking into account the above findings, **the second objective** of this work is **the development of a systematic process of the third step of the TOC-DBR methodology for MTO environments to facilitate its step-by-step application to improve system performance.**

The literature review has also failed to identify studies that analyse the relationship between protective capacity and protective inventory in different manufacturing environments, thus defining the **third research objective, which is to analyse the relationship between protective capacity and protective inventory in different environments.**

In addition, there are questions about how and to what extent the factors affecting the subordination of non-BN resources affect the BN.

From the literature review, it appears that protective capacity and protective inventory play a key role in system performance. However, authors such as Tu et al. (2005) conclude that it is very difficult to determine the correct protective capacity. Using the same line of argument, Blackstone and Cox (2002) point out that there is no mathematical approach to defining the protective inventory or protective capacity. While an adequate level of protection is necessary to reduce the impact of statistical fluctuations in the system, the difficulty lies in defining the "adequate" protective inventory and capacity. Other authors, such as Caridi et al. (2006), conclude that this additional capacity has a cost, so further research is needed.

Taking into account the difficulty in sizing the necessary protective capacity, the **fourth objective** of the research is defined: **to define how to size and manage the protective capacity of non-BN resources so that the system remains stable over time.**

In conclusion, the literature has shown the need to not only implement the systematic process of the third step of the TOC-DBR methodology for MTO environments but also to manage system protection.

The research objectives establish the appropriate RQ for this doctoral research work.

According to Yin (2018), the definition of the RQ is a key starting point for choosing the appropriate research methodology.

Furthermore, the selection of research strategies and tactics depends on the type of RQ to be answered (Robson & McCartan, 2016).

The RQ of this PhD research project is presented as follows:

RQ1. How can non-BN resources of a production system in an MTO context be managed both systematically and by means of TOC-DBR to enhance performance?

- RQ1a. How should the level of protective capacity of non-BN resources be defined?
- RQ1b. How can the protective capacity be managed?

3.2 Research methodology

The term "research methodology" is a widely employed concept in scientific literature, but its meaning varies among researchers. The definition of research methodology in this thesis is based on key authors such as Clough & Nutbrown and Freedman (2012; 2000), who argue that a good research methodology should endure throughout the research, justify the research assumptions and facilitate a comparison between these assumptions and existing philosophical paradigms.

Furthermore, the research methodology should include the process used to formulate RQs and, consequently, justify the selected research strategies, such as action research or CSs, as well as the methods or tools used to collect and analyse data, such as interviews or triangulation. These aspects of the research methodology are also encompassed within the concept of the research design, as indicated by Robson & McCartan (2016).

The literature review conducted in this study confirmed the need for further empirical research in this field. Therefore, the first research objective was **to provide empirical CSs on the implementation of the TOC-DBR methodology in MTO environments**. This research field falls within the domain of operations management, which encompasses two methodologies for theory development depending on the research purpose: formal methodology and empirical methodology. While formal sciences use deductive methods to develop theories, empirical sciences employ inductive methods to create these theories. Sax (1968) explained this distinction as follows: *"if a theory is based primarily on deductive rules, it is called formal science; the objective is to distinguish it from other areas of knowledge that depend mainly on empiricism and induction: the so-called empirical sciences"* (p. 68).

Wacker (1998) concluded that no research category or method is superior to others methods in creating a solid theory in operations management. Each research method serves a different but equally important purpose in developing the theory of operations management. Formal methodologies are aimed at developing theories with internal coherence via logical analysis, whereas empirical methodologies provide empirical verification of models while offering evidence for the development of new theory.

Several authors have claimed that operations management is a problem-solving-oriented research discipline that can generate abundant new knowledge via interaction with real-world professionals, such as Lewis (1998), McCutcheon & Meredith (1993) and Van Aken et al. (2016). Therefore, in response to the numerous calls for more empirical research in this field, the authors chose to adopt empirical methodology as the primary approach for this project. This methodological choice, as well as the type of research questions, influenced the subsequent selection of research strategies for the design and programme of the study.

3.3 Research design

According to Robson & McCartan (2016, p. 71) *"Design is concerned with turning research questions into projects".*

For this reason, it is important to precisely define the scope of the research and the appropriate methodology in terms of effectiveness. This approach involves the creation of the research process itself (Robson & McCartan, 2016; Voss et al., 2002; Yin, 2018).

Authors such as Robson & McCartan (2016) or Hernández-Sampieri et al. (2018) define two general aspects for the development of research: the definition of the strategy to be followed and the definition of the tactic.

- Research strategy definition: General framework of research and orientation adopted to answer the RQs.

  a) Identification of the research purpose.

  b) Selection of the strategy.

  c) Selection of the unit to be analysed.

- Research tactic definition: Scientific method proposed for the development of the investigation.

a) Definition of the data collection method

b) Analysis and evaluation of the collected data

3.4 Research strategy

Based the most relevant aspects outlined in the previous section, this chapter is divided into three sections, defined as part of the research strategy. Section 3.4.1 describes the purpose of the research, Section 3.4.2 addresses the research strategy and type selection, and Section 3.4.3 defines the unit of analysis of this work.

3.4.1 Identification of the research purpose

To define the research strategy, it is first necessary to define the objective or purpose of the research. According to Robson & McCartan (2016), the purpose can be exploratory, descriptive or explanatory (Table 4).

The exploratory type of research is characterised by its focus on examining a research problem that has received minimal attention, raises numerous questions or has not been adequately addressed. The primary objective of exploratory research is to gain a better understanding of phenomena from a new perspective. While exploratory research is typically qualitative in nature, it does not necessarily have to be limited to qualitative methods (Robson & McCartan, 2016).

On the other hand, the descriptive type of research is aimed at providing a detailed specification of the properties, characteristics and profiles of individuals, groups, communities, processes or objects that are the focus of analysis. Descriptive research involves collecting and presenting information about the subject of investigation in a comprehensive manner. Descriptive research requires a thorough understanding of the situation being investigated, enabling researchers to identify the relevant aspects on which data should be collected. Descriptive research can employ both qualitative methods and quantitative methods, depending on the nature of the RQ and the available resources (Robson & McCartan, 2016).

The explanatory type of research is aimed at understanding the relationship between two or more concepts, categories or variables within a specific context. Explanatory research surpasses merely describing phenomena and seeks to explain the underlying mechanisms and reasons of a situation or problem. Explanatory research focuses on identifying causal relationships and determining how changes in one variable may influence changes in another variable. Both qualitative methods and quantitative methods can be employed in explanatory research, depending on the RQ and the nature of the variables that are being examined (Robson & McCartan, 2016).

Table 4. Main characteristics of research types. Note: based on (Robson & McCartan, 2016)

TYPE	CHARACTERISTICS
Exploratory	To examine a research problem that has been underexplored and raises many questions or has not been addressed. Exploratory research is usually, but not necessarily, qualitative.
Descriptive	To specify the properties, characteristics and profiles of the individuals, groups, communities, processes or objects that are the object of analysis. Descriptive research requires extensive prior knowledge of the situation to be investigated or described. Descriptive research can be qualitative and/or quantitative.
Explanatory	To understand the relationship between two or more concepts, categories or variables in a given context. Explanatory research seeks to explain a situation or problem, usually in the form of causal relationships. Explanatory research can be qualitative and/or quantitative.

The following objectives have been defined for this research project:

1- To provide empirical CSs on the implementation of the TOC-DBR methodology in MTO environments

2- To develop a systematic process for the implementation of the third step of the TOC-DBR methodology for MTO environments to facilitate its step-by-step application and thus improve system performance
3- To analyse the relationship between protective capacity and protective inventory in different environments
4- To define the procedure for sizing and managing the protective capacity of non-BN resources to ensure that the system remains stable over time

Taking into account the defined RQs and stated objectives, the research will be mixed. Designing a systematic process to implement the third step TOC-DBR is a field that has not been extensively investigated, so the purpose will be exploratory. On the other hand, the TOC-DBR methodology is well studied and documented, so in this aspect, the purpose of the research will be descriptive.

3.4.2 Research strategy and type selection

Research strategies can be designed as quantitative research, qualitative research, or a combination of both, which is known as mixed methods research. Quantitative research relies on mathematical or numerical data and employs statistical or computational techniques to analyse patterns of behaviour or test theories (Robson & McCartan, 2016). In contrast, qualitative research involves an evolving design during data collection and often utilises open-ended questions to gather rich, descriptive data (Robson & McCartan, 2016). Mixed methods research takes into account both points of view while seeking a viable middle ground solution to many research problems. Mixed methods research is, broadly speaking, an approach to theoretical and practical knowledge that attempts to consider multiple points of view, perspectives and positions, always including both qualitative research viewpoints and quantitative research viewpoints (Johnson et al., 2007). Mixed methods purposefully combines quantitative research methods and qualitative research methods to address a RQ that is aimed at achieving more comprehensive and insightful results than what could be obtained through either method alone (Danielle et al., 2022).

On the other hand, Yin (2018) distinguishes five categories of strategies to address research: experiments, surveys, archival analysis, history and CSs.

The importance and selection of these five categories depends on three conditions: the form of the research approach, the control the researcher has over the actual behavioural events and the degree of attention paid to contemporary events in contrast to wholly historical events.

Table 5. Relevant situations for different research methods. Note: based on Yin (2018)

Strategy	Form of RQ	Requires control over behavioural events	Focuses on contemporary events
Experiment	How and why?	Yes	Yes
Survey	Who, what, where, how many and how much?	No	Yes
Archival analysis	Who, what, where, how many and how much?	No	Yes/no
History	How and why?	No	No
CS	How and why?	No	Yes

The five strategy methods shown in Table 5 have a common question related to 'how phenomena occur'. The survey collects information in a standardised way to describe the environment in which the phenomena occur based on statistics. Experimentation and CSs are oriented to identify the cause of the phenomenon, in the case of experimentation, provoking scenarios to understand the phenomenon. In the case of CSs, it is not necessary to have control over the events, but it is possible to provoke the scenarios to observe the effect on the phenomenon. Archival analysis and historical research often involves understanding the evolution, development and practices of a particular industry. Archival analysis can provide valuable historical context by examining industry-related documents, records and organisational material, while historical research allows the history of specific industrial organisations to be analysed. This approach can help researchers better understand the historical factors, trends and events that have shaped the sector.

During the research project, different real scenarios are analysed; therefore, the survey as a research strategy is rejected. Archival and historical analysis methods are also rejected as the scenarios to be analysed are current and complex environments.

Experimentation and CSs have aspects in common, but the approach and mode of action are different. In experimentation, it is necessary among other things to be able to manipulate the factors, to control the experimental environment, to have homogeneous experimental units and to obtain an experimental sample that is significant enough to mitigate the effect of noise on the signal. Therefore, replicated situations would be necessary, and unnecessary and unrealistic scenarios could be required. In this research, it is not possible to create replicas for comparison; therefore, the experimental strategy lacks logic.

This research will analyse several real-life scenarios and carry out various simulations of these real-life environments with Simio software. As a result of the scenarios, both quantitative data and qualitative data will be obtained, resulting in mixed methods research. Authors such as Mertens (2005) define that data collection in mixed methods research can be either parallel or sequential. In parallel data collection, qualitative and quantitative data are simultaneously and independently analysed. Sequentially, one type of data serves as a basis for the collection of another type of data.

In the case of this research, the results of one scenario will be the basis for the design of the next scenario, so the research method will be mixed and sequential.

Additionally, to obtain the necessary information, design the systematic implementation process of the third step of TOC-DBR and answer the posed RQ, the single CS approach is selected as the research methodology to investigate a current phenomenon in a real environment (Yin, 2018).

As the most cited author in case-based research, Yin (2018) claims that CS research is the most appropriate strategy if the following aspects are present:

- The researcher is not a mere observer; that is, he is an active part of the process, and his observations can be used to generate new theories. In the present investigation, the researcher takes an active part in the process.

- The phenomenon being investigated is contemporary, and the research will be carried out in a real context.

- The research will use different sources (bibliographies, existing documentation in the company, etc.) to identify the characteristics of the model and its implementation.

For the CS strategy to be appropriate, it must be systematically carried out (Yin, 2018) following the three-step outline in Figure 13.

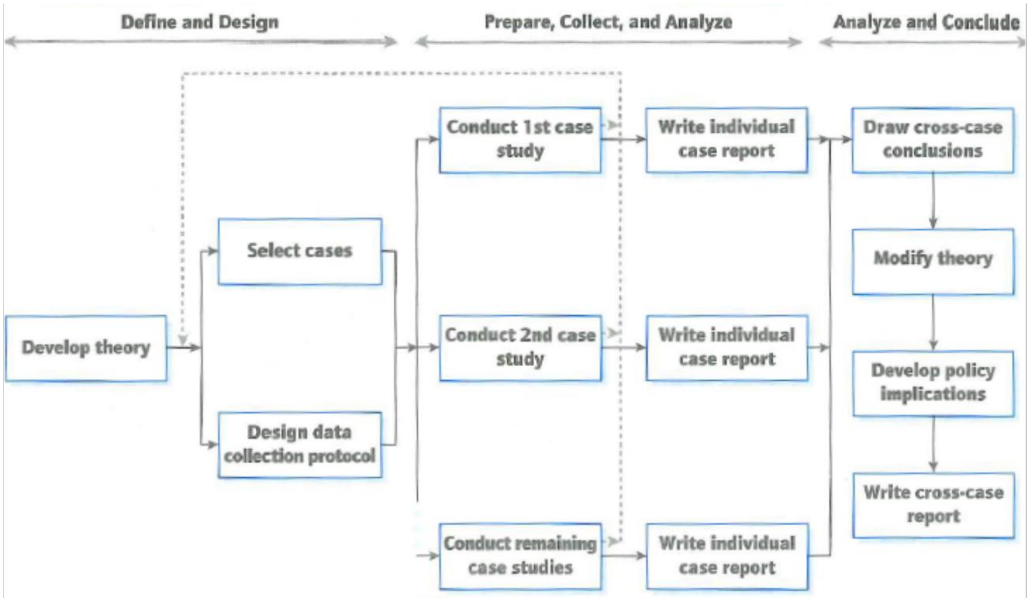

Figure 13. Multiple-CS procedure (Yin, 2018, p. 58)

1- Definition and design the process to be analysed includes the development of the theory, the identification of the knowledge and sources of information necessary to select the method of selection for the CSs. In addition, the data collection is planned.

2- Preparation, collection and analysis of the information generated during the execution of the operational part of the CSs. The data collection method is the key to the success of the CSs.

3- Analysis and conclusions. An overall analysis of all cases is carried out. From this analysis, possible modifications of theories are proposed and new replications are made.

3.4.3 Unit of analysis

The selection and representativeness of samples or CSs play a crucial role in CS methodology. In academic research using CSs, samples are often chosen based on their theoretical significance rather than their statistical representation (Eisenhardt, 1989). However, when generalising conclusions or comparing results with varying factors, the representativeness of the sample becomes highly important, as in this study.

Yin (2018) proposed a preliminary approach for sampling cases in research scenarios similar to the present investigation, in which two factors are considered (Figure 14). The first factor is the number of distinct contexts, which are referred to as "scenarios," in which the system under study exhibits different behaviours (e.g. companies, business units, departments, etc.). The second factor is the type of knowledge to be examined: holistic if it pertains to the entire context and cannot be found in its parts or embedded if it is represented in samples obtained from the context (i.e. by selecting and replicating multiple samples to achieve representativeness of the context).

For holistic scenarios, there is one case per context. If the scenario is not holistic, multiple cases can be included within each context to optimise the data collection for a better understanding of the context. Yin (2018) recommended employing multiple cases primarily to obtain robust conclusions. However, he cautioned that conducting numerous cases may not always be feasible due to resource constraints (Yin, 2018).

This research will be holistic in several cases. Each scenario is represented as a different context in which the research will be carried out, so that the findings will serve as input for the next CS until the systematic process of implementing the third step of TOC-DBR is developed. The research is holistic because the typology of knowledge to be examined is in the whole context (in the total implementation of the process), not in the parts of the context. The research is also multi-case because it is carried out in several cases.

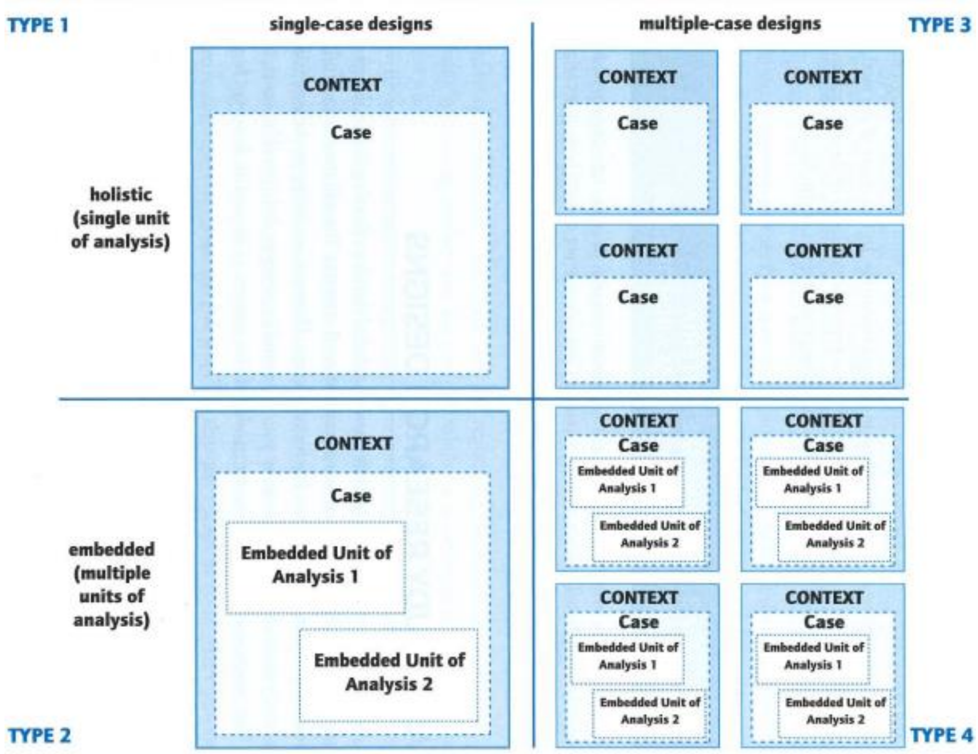

Figure 14. Basic types of designs for CSs (Yin, 2018, p. 48)

The present four case studies have been carried out based on two companies in the Basque Country, where the implementation of the third step of the TOC-DBR methodology in MTO environments has been analysed. The other two case studies involved simulations based on the first company, in which different environments have been simulated to analyse the impact of different factors on the system.

In Chapter 4 Fieldwork, all the information about the four case studies is detailed.

3.5 Research tactics

This section outlines the research strategies employed in this study. In particular, section 3.5.1 provides an overview of the data collection methods, and section 3.5.2 elucidates the approach to analysing and interpreting the data gathered from the CSs.

3.5.1 Definition of the data collection method

As mentioned in section 3.4.2 Research strategy selection and type selection, this dissertation uses a mixed sequential research strategy and therefore data collection is carried out in a different way. Both qualitative data collection and quantitative data collection are employed. Each of the phases is described below.

3.5.1.1 Qualitative data collection

The data collection methods in qualitative research vary depending on the nature of the study. Yin (2018) provides a summary of these methods, as shown in Table 6. These methods are specifically designed to capture detailed and contextual information, allowing researchers to gain a comprehensive understanding of the RT.

Table 6. Summary of different data collection methods for qualitative research. Note: based on Yin (2018)

SOURCE OF EVIDENCE	STRENGTHS
Documentation	Letters, e-mail correspondence, administrative documents, etc. Helpful in verifying the correct spelling of titles or names of organisations that might have been mentioned in an interview. Can provide other specific details to corroborate information from other sources. Inferences can be made, but it is important to treat them as clues worthy of further investigation.
Archival records	Computer files and records such as service records, organizational records, maps, survey data, etc. In some CSs, records can become the object of extensive retrieval. In other CSs, they may have passing relevance.
Interviews	One of the most important sources of CS information. Comprise guided conversations rather than structured queries.
Direct observation	To observe the natural setting of the case that is going to be analysed.
Participant-observation	A type of observation where the viewer participates in the CS by participating in the events.
Physical artefacts	Technological device, work of art or other physical evidence.

Among the data collection methods, interviews are usually the main source of data in CSs (De Massis & Kotlar, 2014; Eisenhardt & Graebner, 2007). Interviews provide direct contact with key actors in the implementation, offering the opportunity to gain an in-depth understanding of the case. For this reason, in this doctoral thesis, interviews are used as the primary source of information. Additionally, interviewing different profiles within a company provides a different perspective on the same topic.

In addition to interviews, archival records and documents have also been used to collect specific data on different indicators. These documents serve as evidence to support the information gathered in the interviews.

Triangulation is employed to enhance the credibility of data (De Massis & Kotlar, 2014; Patton, 1990). The use of multiple data sources provides the opportunity to observe the same phenomenon from different angles, rendering the findings more convincing and accurate (De Massis & Kotlar, 2014; Jick, 1979; Pettigrew, 1990; Stake, 2013; Tracy, 2010; Yin, 2018).

Once interviews are selected as a method of qualitative data collection, Robson & McCartan (2016) identifies three different types of interviews: structured, semi-structured and unstructured, as presented in Table 7. These types of interview offer varying levels of flexibility and guidance in the questioning process, allowing researchers to tailor their approach according to the research objectives and the desired depth of information.

Table 7. Summary of the types of interview. Note: based on Robson & McCartan (2016)

INTERVIEW TYPE	DESCRIPTION
Structured interview	Is a questionnaire with fixed questions in a predetermined order and standardised application, whereby responses to most of the questions have to be selected from a small list of alternatives.
Semi-structured interview	Has predetermined questions, but the order can be modified based on the perception of interviewer of what appears most appropriate. Question wording can be changed and explanations given; particular questions that seem inappropriate for a particular interviewee can be omitted or additional questions can be included.
Unstructured interviews	The interviewer has a general area of interest and concern but allows the conversation to develop within this area. The interview can be completely informal.

Semi-structured interviews were used to collect the data for this research. This type of interview proposes a set of questions while offering the opportunity to add more questions at any given time to obtain more information. Semi-structured interviews provide flexibility, allow the interviewer to further explore or clarify any misunderstandings, and encourage cooperation and rapport (Robson & McCartan, 2016).

In designing the questions for these interviews, the role of the interviewee was taken into account. To identify which persons were to be interviewed and the questions to be asked of each interviewee, a modified Delphi study was conducted. This study consisted of validating the roles and questions with experts in the implementation of the TOC-DBR methodology. The following steps were followed

1. The implementation to be analysed was identified.
2. The TOC-DBR experts who had implemented the methodology in the analysed companies were identified.
3. The profiles of the interviewees were identified to obtain the key information of each case and to define the questions to be asked of each interviewee.
4. Both the interviewees and the questions asked in each interview with the TOC-DBR experts identified in step two were validated.

5. Feedback was received, and changes were made based on the experts suggestions.

To collect as much information as possible, we recorded the interviews. Recording provides a permanent record and allows us to concentrate on the interview (Robson & McCartan, 2016). These recordings were considered confidential and were not included in this research.

3.5.1.2 Quantitative data collection

Quantitative research is characterised by its logical and linear structure, where hypotheses are formulated as expectations regarding potential causal relationships between two identified concepts. The focus is determining these causal links specified by the hypotheses, which leads to either accepting or rejecting the proposed relationships. Therefore, quantitative research places great importance on methodology, procedures and statistical measurement and analysis of data to establish relationships between two different sets of data. The measurement of variables in quantitative research often leads to quantifiable conclusions (Eldabi et al., 2002).

For this dissertation, the simulation of a real environment with Simio software has been employed as a methodology to obtain quantitative data.

Simulation is indeed a commonly utilised methodology in operations research and management science. Simulation involves utilising computer programmes or algorithms to create models that represent real-world systems or processes. These models are then numerically evaluated by running simulations to observe and analyse their behaviour. During the simulation process, data are collected to estimate and understand the desired characteristics or performance measures of the model. The data gathered from the simulations are used to analyse the model's behaviour, validate its accuracy and make informed decisions or recommendations based on the results (Law & Kelton, 2006).

Simulation models can be classified into three different dimensions. An overview of these dimensions is provided in Table 8 (Law & Kelton, 2006).

Table 8. Summary of the classification of simulation models. Note: based on Law & Kelton (2006)

MODELS	DESCRIPTION
Static versus dynamics simulation models	A static simulation model is a representation of a system at a particular time in which time plays no role.
	A dynamic simulation model is a representation of a system as it evolves.
Deterministic versus stochastic simulation models	A deterministic simulation model does not contain any probabilistic (i.e. random) components
	A stochastic simulation model has at least some random input components.
Continuous versus discrete simulation models	A continuous simulation model concerns the modelling of a system over time by a representation in which the state variables continuously change with respect to time.
	A discrete simulation model is a system that evolves by a representation in which the state variables instantaneously change at separate points in time.

The simulation models that will be employed in this thesis are discrete, dynamic and stochastic and henceforth are referred to as discrete event simulation models. This nomenclature is applied because deterministic models are a special case of stochastic models and the restriction to stochastic models does not imply any loss of generality. Discrete event simulation focuses on modelling the sequence of events and activities that occur over time, allowing for the representation of complex processes with distinct events and interactions. By using a discrete event simulation model, the researchers can accurately model and simulate the discrete events and activities that occur within the system under investigation. This simulation includes capturing the timing, sequencing and dependencies of events, as well as the resources, constraints and rules governing their occurrence.

In the context of the real CS, discrete event simulation allows a detailed analysis of the system's operations, including the scheduling of events, utilization of resources, BNs and overall system performance. Discrete event simulation enables the researchers to analyse the impact of different scenarios, policies or interventions on the system's behaviour and performance, providing valuable insights and decision support.

To design the simulation model, specifically a discrete event simulation in this case, it is necessary to follow a series of steps to ensure the quality of the model. Figure 15 illustrates the steps defined by Law & Kelton (2006) for achieving this objective, which have been employed in the CSs throughout this doctoral thesis.

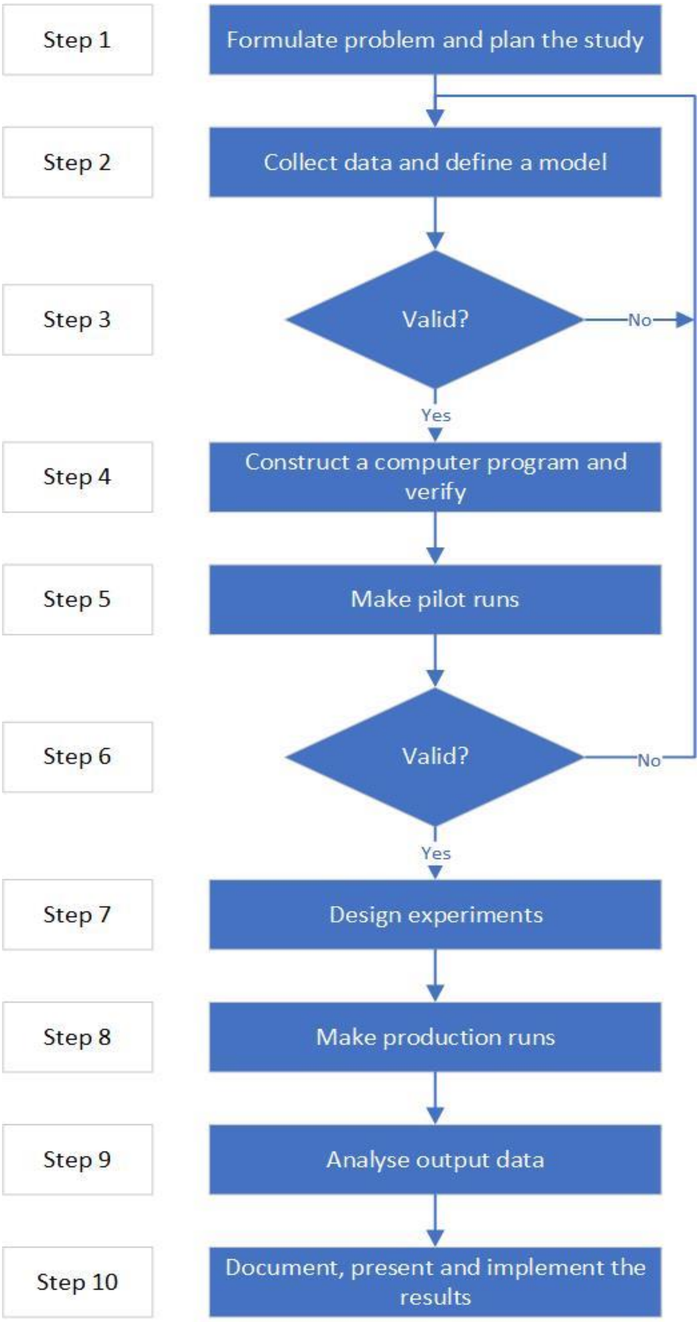

Figure 15. Steps of a simulation study. Note: based on Law & Kelton (2006)

According to Law & Kelton (2006), the first step in problem formulation involves establishing the study objectives and determining the specific issues to be addressed, while also considering the availability of necessary resources for conducting the research. The second stage, as shown in Figure 15, is data collection. Data are collected if they exist and align with the study objectives. The third step involves validation of the collected data. Once the data are validated, the fourth step is to construct a computer model based on the conceptual model. Next, in step five, a pilot test is conducted. However, it is suggested to translate the conceptual model into a computerised model before proceeding to step six, which involves verification and validation. Note that the validation and verification process should be carried out throughout the entire study. Stages seven to ten involve the design of experiments to define different experimentation alternatives, production runs to obtain performance data for the system designs of interest, analysis of results using statistical techniques to analyse the production run data and application of the model results.

3.5.2 Analysis and evaluation of the data collected

As discussed in section 3.5.1, this section is also divided into a qualitative part and a quantitative part.

3.5.2.1 Analysis and evaluation of the collected qualitative data

Once the interviews have been conducted and the data have been collected, the data processing phase begins. The following four steps are performed to carry out the data processing (De Massis & Kotlar, 2014; Miles & Huberman, 1994; Tesch, 2013):

1. Data reduction: The collected data are selected, focused, condensed and simplified in preparation for data analysis.
2. Data visualisation: An organised system is created for storing the data to facilitate identification and extraction of information.
3. Data categorisation: Different categories of information are created to enable comparisons and distinctions.
4. Data contextualisation: The collected data and external contributions are combined while identifying links and connections.

These steps help streamline and comprehend the collected data, ensuring that the data are organised and ready for further analysis and interpretation.

Yin (2018) suggested four different techniques for analysing and evaluating data in CS research: building on theoretical propositions, developing a case description, using qualitative and quantitative data and examining rival explanations. Furthermore, once the data analysis is completed, a global evaluation is conducted to determine if the data from all cases provide sufficient evidence to support the initial theory (Johnston et al., 1999).

CS research has been criticised for lacking objectivity and methodological rigour. To address this criticism, (Hirschman, 1986; Johnston et al., 1999) proposed four aspects to avoid subjective interpretation of evidence and data, ensuring theory-based, systemic and rigorous conclusions:

- External validity: This aspect is also known as study replication. The authors propose analysing the same phenomenon in different contexts to determine if the results lead to the same conclusion. In this thesis, four case studies were selected, in which the TOC-DBR methodology was applied, allowing us to identify how non-BN resources were subordinated to the BN.
- Internal validity: To determine the credibility of a specific interpretation, the authors suggest subjecting the interpretation to scrutiny by the people on which it is based and gathering their responses regarding its authenticity. In this study, the report of each CS was supervised and validated by the analysed company as well as the practitioners involved in the implementation of the TOC-DBR methodology. This step ensured that the information collected in the interviews was accurately reflected in each CS.
- Reliability: This aspect examines the temporal stability and internal consistency of measurements made on a variable. To achieve this aspect, the author proposes to ensure internal validity and then perform triangulation with multiple sources. These tasks are carried out in the present study. The cases have been internally validated, and data collection has involved triangulation among semi-structured data, archival records and documentary sources.

- Objectivity: This aspect ensures that the interpretation of CS results is based on observable phenomena and is not influenced by personal biases. To address this aspect, the authors suggest subjecting all study results to an external auditor who evaluates whether the results appear logical and unbiased. In this research, the CSs, as well as the cross-CS, were examined and assessed by an expert in the TOC-DBR methodology who did not participate in or have prior knowledge of the analysed CSs.

3.5.2.2 Analysis and evaluation of the collected quantitative data

In this dissertation, the analysis of quantitative data involves the use of analysis of variance (ANOVA) and Tukey's post hoc test. The ANOVA is chosen as it allows the comparison of multiple groups and the assessment of overall variance, while Tukey's test is employed for pairwise comparisons between two groups and to control for Type I error inflation. These statistical techniques provide robustness to multiple comparisons and offer objective measures for interpreting group differences (Driscoll, 1996).

3.6 Research programme

The research programme followed in this thesis is represented in Figure 16. The research purpose has been exploratory and descriptive. Regarding the research strategy, a sequential mixed methods approach has been employed using a holistic multiple-CS. Qualitative data have been collected via semi-structured interviews, documents and archival records. Additionally, for the collection of quantitative data, simulations of a real environment have been conducted. The analysis and evaluation of qualitative data have been carried out using theoretical propositions. Furthermore, to ensure objectivity in the interpretation of data, internal and external validation, triangulation and an external audit have been conducted. For the analysis and evaluation of quantitative data, ANOVA and Tukey's post hoc test have been performed.

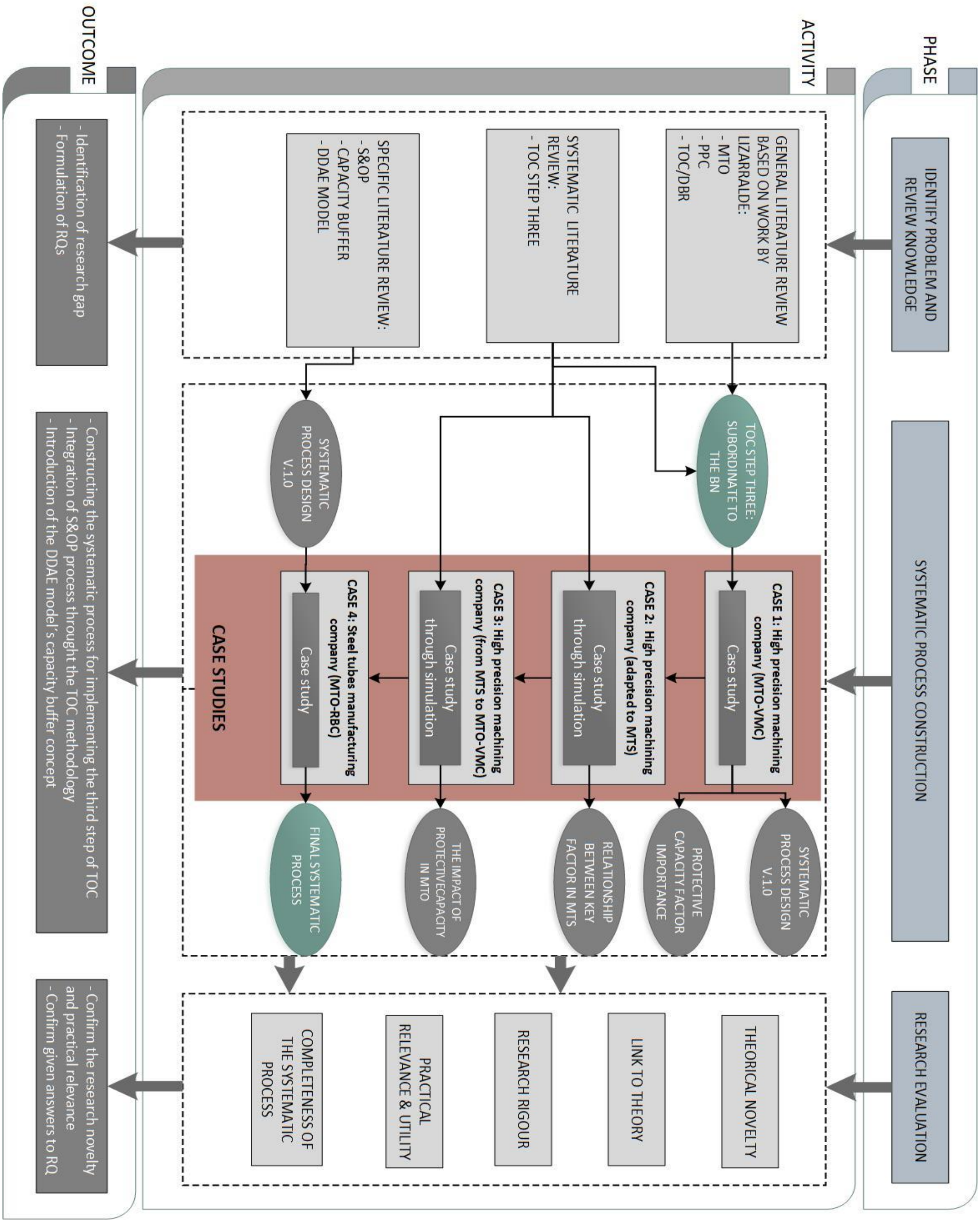

Figure 16. Research programme: Phases, activities and outcomes

Chapter 4

4 Fieldwork

This chapter describes the fieldwork carried out to answer the posed RQs based on the research design and programme detailed in chapter 3.

The fieldwork consists of four CSs. In CS1 and CS4, which are based on two real industrial implementations, Lizarralde et.al. (2019, 2020) applied the TOC-DBR methodology following the systematic process of the first two stages. CS2 and CS3 are simulations based on CS1.

Each of the CSs makes different contributions to this thesis. Figure 17 shows a summary of the fieldwork carried out and the contribution each CS makes to the six contributions to this thesis. Furthermore, as shown in the figure, the output or contributions of each of the CSs is the input to the next CS.

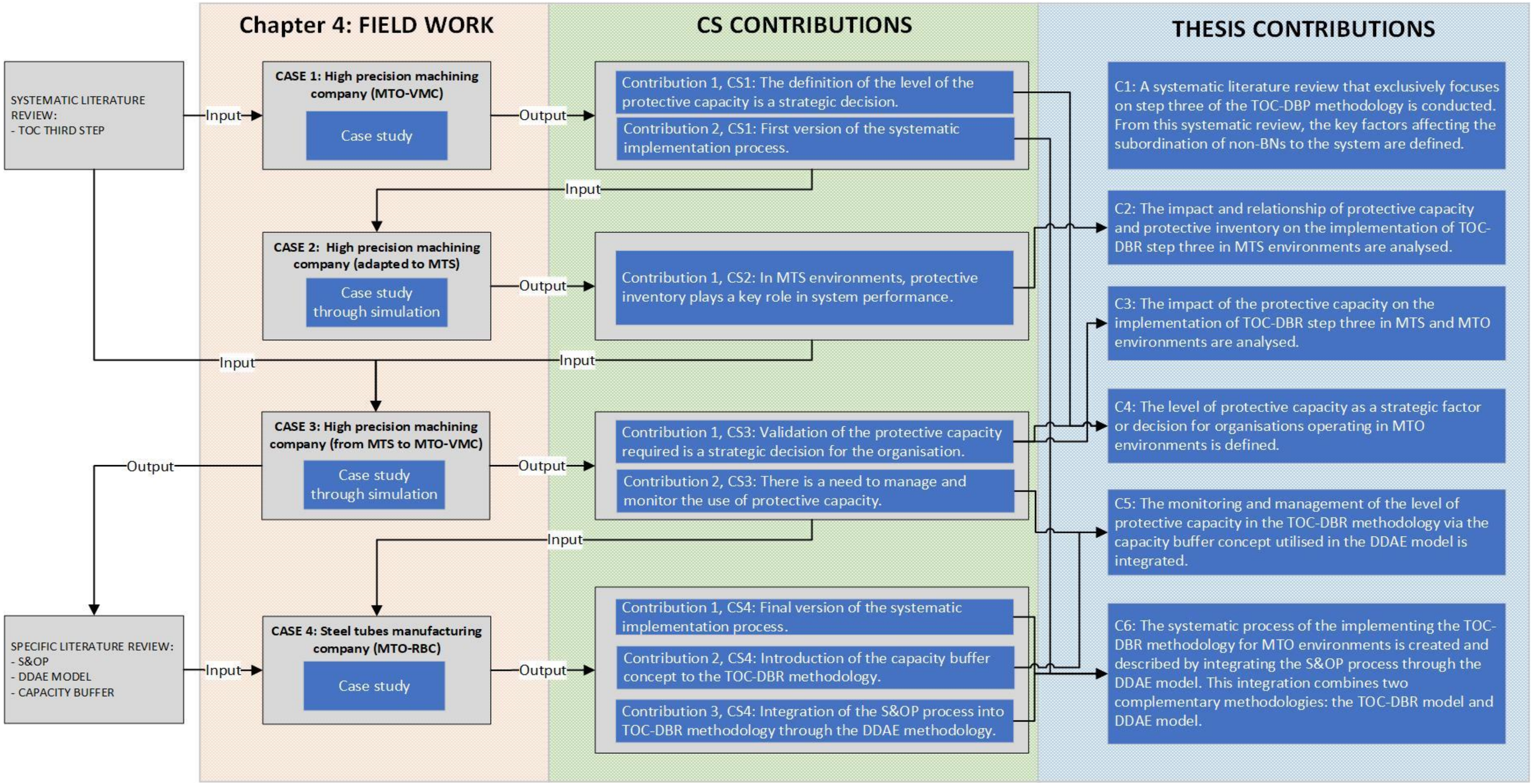

Figure 17. Summary of fieldwork and CS contributions to the dissertation

The results and contributions of the research have been evaluated and published in four journal articles and three international conferences (details in Table 9).

Table 9. Research programme CS characteristics and related publications

Case study	Characteristics	Related publications
CS1	High-precision machining sector (MTO-VMC environment)	- Conference proceeding in the 14th International Conference on Industrial Engineering and Industrial Management, Leganes, 2020 - Article published in the Journal of Industrial Engineering Management (Orue et al., 2021)
CS2 Using simulation	High-precision machining sector (adapted to MTS environment)	- Conference proceeding in the 15th International Conference on Industrial Engineering and Industrial Management, Burgos, 2021
CS3 Using simulation	High-precision machining sector (from MTS to MTO-VMC environment)	- Article published in DYNA Management (Orue et al., 2022). - Article published in DYNA (Orue et al., 2023)
CS4	Steel tubes manufacturing company (MTO-RBC environment)	- Conference proceeding in the 16th International Conference on Industrial Engineering and Industrial Management, Toledo, 2022 **(Best Paper Award)** - Article published in the Journal of Industrial Engineering Management (Orue et al., 2023)

4.1 Structure of the case studies

The CSs are organised according to a homogeneous structure, the main levels of which are described below. The CSs differ somewhat whether they are real CSs or simulation CSs.

1- **Introduction to the company:** The main characteristics of the company, as well as the particular context surrounding it when the case analysis was developed, are described. The company characteristics provide a detailed overview of the company's size, main processes, operations, etc.

   In the case of the simulations, the simulation model and characteristics of the simulation are described.

2- **Process of implementing DBR:** How the TOC-DBR process was implemented in the CS and the results are described.

   In the case of the simulations, the simulation assumptions and implications of the simulation are described.

3- **Analysis of the third step of the TOC-DBR methodology:** The purpose of the DBR application section is to analyse how the third step was implemented and thus to obtain information for the design of the systematic process of the third step. These analyses are based on semi-structured interviews with managers and implementers of the process.

   In the case of the simulations, the experimental design, its experimental factors and the description of the performance measures are presented.

4- **CS results:** The final section of each CS summarises the main results of the implementation of the process for each company.

   In the case of the simulations, the most important quantitative results of the experimentation are obtained.

5- **CS contributions:** The CS contributions section entails the most relevant information and contributions of the CS to the thesis, both theoretical and practical.

4.2 Case study 1

4.2.1 Introduction to the company

The CS1 company is a prominent player in the high-precision machining market. Situated in the Basque Country of Spain, this company specialises in delivering tailored solutions to a global customer base. The company's expertise lies in providing custom-made products such as vacuum chambers, complex structures and pressure vessels. Their manufacturing capabilities encompass various technologies, including cutting, shot blasting, pickling and passivating, press forming, welding, painting and machining.

The company is organised in a functional way (job shop) and has a highly complex management due to the casuistry of its material flows. Figure 18 shows the material flow of CS1.

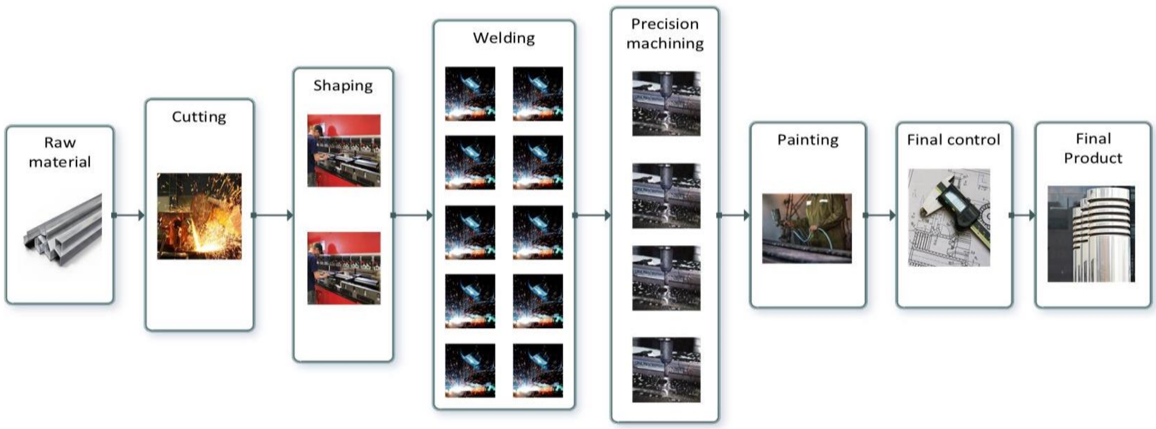

Figure 18. General material flow in CS1. Note: based on Lizarralde et al. (2020)

4.2.2 Drum-buffer-rope implementation

Lizarralde et al. (2020) discovered that the planning process in the CS company had primarily focused on maximising the performance and production of individual sections within the company with a localised perspective. Consequently, each section developed a weekly production plan based on "hours worked per day" as the main objective. However, this approach led to difficulties in meeting customer delivery expectations, despite the management team believing that the existing capacity was sufficient to complete the work within the specified due dates. To address this issue, the researchers implemented a systematic process for the first two steps of the TOC methodology (Lizarralde et al., 2020).

The first step involved conducting a comprehensive system analysis and examining various aspects such as the manufacturing process, resource capacities, batch policies, metrics, and part routes. Following this analysis, a load versus capacity analysis was performed to compare the demand placed on the resources during a specific period against their actual capacity. The aim was to identify any imbalances and to assess the system's capability to meet the demand. Subsequently, a strategic decision was made regarding where to place the constraint within the system. In the case of the CS company, precision machining was chosen as the BN resource. Scheduling policies were defined to effectively exploit the system, particularly determining when to schedule the utilisation of the BN and how to subordinate the remainder of the system accordingly.

Crucially, consideration was given to ensuring that the operations preceding and succeeding the BN had sufficient capacity, as this was a critical factor in the subordination process. The resulting design of the DBR solution is illustrated in Figure 19.

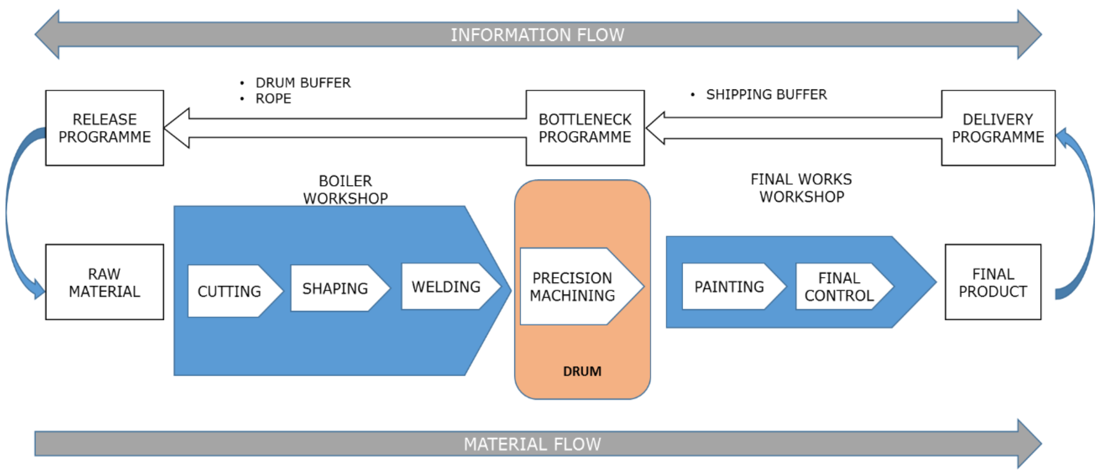

Figure 19. General material flow in the CS company (Lizarralde et al., 2020, p. 117)

The most relevant results obtained after the DBR implementation, including the systematic process of the first two TOC steps, are presented as follows: (1) service level increased from 50% to 70%, (2) manufacturing maturity period decreased by 10% and (3) inventory level (WIP) decreased by 20% (Lizarralde et al., 2020).

4.2.3 Theory of constraints – drum-buffer-rope step three analysis

The data collection for this study were conducted via semi-structured interviews involving four managers from the CS company. The focus of these interviews was the implementation approach, particularly the third step of the TOC. The respondents were asked about their experiences and challenges encountered during implementation of the designed model. The interviews revealed that the managers faced difficulties in implementing the model as intended. One of the prominent challenges identified was related to the BN programme not receiving materials from previous operations, despite supposedly having sufficient capacity. This issue stemmed from the significant product diversity within the company. The wide range of products introduced variability into the production system, making it challenging to accurately determine the workload and capacity. Precise estimation of process times became difficult due to the diverse nature of the orders. For instance, the order book consisted of a small number of orders that were highly diverse, ranging from pumps for hydroelectric power stations to vacuum chambers for scientific projects.

As previously mentioned, the variability in the production system made it challenging to accurately predict resource loads. This variability introduced unpredictability to the system, making it difficult to execute the planned work as intended.

To identify the root cause of the problem, a work programme was initiated, and the analysis focused on determining which non-BN resource was unable to produce the planned work as intended. This analysis revealed that there was an accumulation of material in the welding area, leading to a shortage of material reaching the BN resource. This issue of material accumulation and subsequent starvation of the BN was specific to the welding area and did not occur for the other non-BN resources.

Taking into account the identified root cause of the material shortage in the BN resource, a decision was made to address the issue by increasing the capacity of the welding area. Specifically, the capacity of the welding area was expanded by adding additional welders, increasing the total number of welders from 30 to 38.

The significant increase in capacity, amounting to a 27% expansion, in the welding area had notable positive effects on the overall system performance. The expanded capacity provided stability to the BN programme, ensuring that the BN remained in its strategically chosen location within the production process.

4.2.4 Case study 1 results

From the systematic literature review of the third step of the TOC-DBR methodology in section 2.4, two key factors have been identified during implementation of step three. These two factors, protective capacity and protective inventory, are responsible for absorbing system variability and eliminating starvation at the BN, which ensures that the system is stable and that the defined results are achieved.

However, after carrying out CS1 and as a result of it, it can be assured that for the analysed company, the key factor for subordinating the system to the BN is the protective capacity (Orue et al., 2021).

In the analysed CS1, initially, the subordination of the system to the BN was not properly carried out because non-BN resources did not have enough of a protective capacity to ensure material flow to the BN. This drawback was due to the greater difficulty in estimating the workload of non-BN resources in MTO scenarios. Thus, the definition of protective capacity is ultimately a strategic decision because the more complex the MTO environment is, the greater the needed protective capacity (Orue et al., 2021).

As previously observed in the outcome of CS1 and in section 2.4, third step systematic literature review, the quantification of protective capacity is a difficult aspect to define. Therefore, the definition of an implementation process will be beneficial.

For this purpose, the first version of the systematic implementation process of the third step has been defined.

This implementation process can be divided into two phases. In the first phase of design, testing and validation, both the BN buffer and the protective capacity for non-BN resources should be defined. Then, to ensure that the defined protective capacity is suitable, the designed DBR model must be implemented and there should be no starvation in the BN. If there is a lack of material, then protective capacity must be increased until it becomes sufficient (Orue et al., 2021).

The second phase is the execution phase. Once the system is defined and validated, it must be monitored and controlled to ensure that the protective capacity remains sufficient over time. The system must control the incoming orders in addition to managing the buffers (Orue et al., 2021).

Figure 20 shows the designed implementation process.

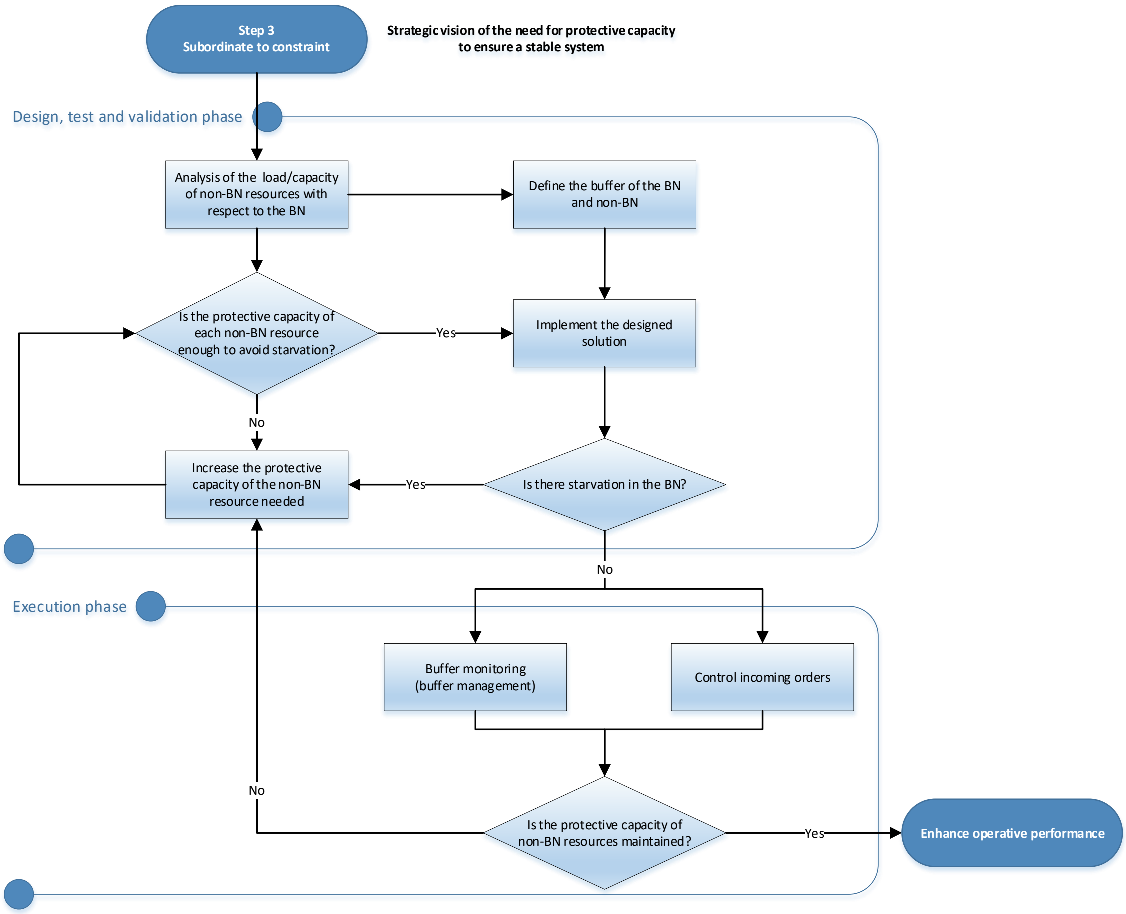

Figure 20. Implementation process of step three (Orue et al., 2021, p. 83)

4.2.5 Case study contributions

Companies working in MTO environments have several difficulties in managing production plants due to the uncertainty of the market, i.e. they cannot accurately predict demand.

From the systematic literature review in step three provided in section 2.4, the two key factors in implementing the third step of the TOC-DBR – protective capacity and protective inventory – are defined.

However, in CS1, it was shown that the key factor for subordinating the system to the BN was the protective capacity. Initially, the subordination of the system to the BN was not correctly carried out because the resources outside the BN did not have sufficient protective capacity to ensure the flow of material to the BN. This drawback was due to the increased difficulty in estimating the workload of non-BN resources in MTO scenarios (Orue et al., 2021).

Consequently, the sizing of protective capacity is a strategic decision of the company. Thus, to ensure satisfactory overall performance, the company must have enough protection against uncertainty at all times (Orue et al., 2021).

From this conclusion, the first contribution of CS1 can be drawn:

`The definition of the level of protective capacity is a strategic decision`

Another conclusion drawn from CS1 is that the quantification of protective capacity is difficult. For this reason the design of a systematic process would help successfully implement the third step of the TOC-DBR methodology. This is the second contribution of CS1:

`First version of the systematic implementation process of the third step`

In addition to the contributions, many issues emerge from CS1 that need to be analysed in the following CSs to answer the defined RQs.

The first issue is the role of protective inventory in different environments and the relationship between protective inventory and protective capacity in these environments. To design a systematic process for implementing the third step, further research is needed to understand this relationship.

This analysis is consistent with the Theory of Constraints Handbook (2010, p. 165), which states that in the future it will be necessary to conduct simulation studies of more complex plants in relation to protective capacity and protective inventory.

In response to this need, in CS2, a simulation is performed to analyse the relationship between the two factors in an MTS environment.

4.3 Case study 2

4.3.1 Simulation model based on case study 1

The designed simulation is based on CS1, in which the systematic process of executing the first two steps of TOC-DBR was implemented.

The analysed system was a continuous flow shop with six workstations, where all parts were processed at each stage and shared the same route. The fourth machine, a precision machine, was selected as the BN as it was selected in the CS1.

As discussed in the previous section, CS2 is aimed at analysing the relationship between protective capacity factors and protective inventory factors in MTS environments. For this reason, the DBR system of the CS1 (Figure 21) has been modelled. For this purpose, numerous requirements have been assumed to simulate the behaviour in an MTS environment. Its variability was mainly attributed to the manufacturing process rather than demand, given that operations were based on the need to meet the forecasts. Spearman and Hopp (1996) identified the following types of variability in DBR systems: natural variability, non-pre-emptive outages and pre-emptive outages. As Ma et al. (2004) discuss, production variability is determined by fluctuations in the quantity of goods produced over time, and MTS environments are preferable to minimise this variability because they facilitate planning and require less facility capacity when production output remains constant.

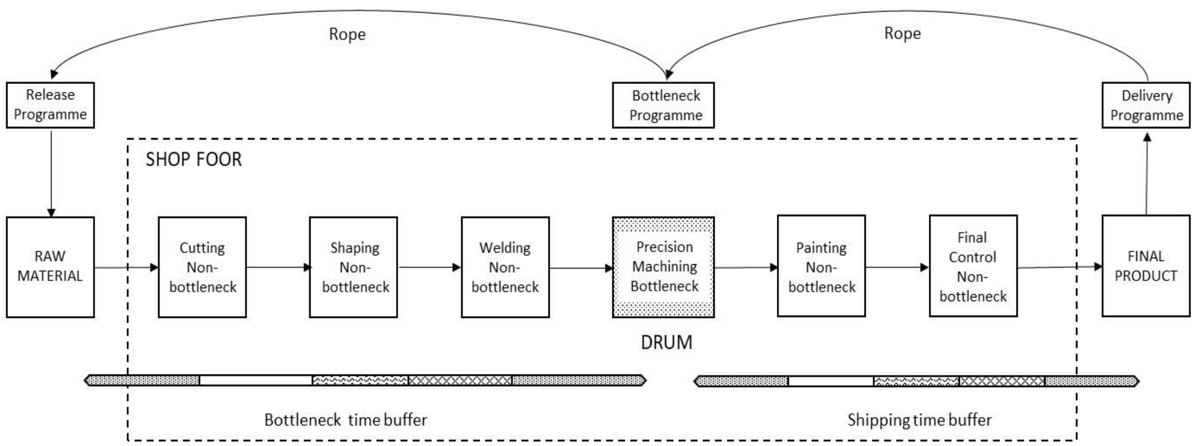

Figure 21. Modelled DBR system

Given these characteristics, a system variability of 12% was defined as a simplification of the model (Orue et al., 2021).

Two strategies, protective inventory and protective capacity, were modelled to compensate for system variability to increase the occupancy level of the BN.

The WIP in the system could be controlled by limiting the number of parts upstream of the BN. A parameter was defined as the ratio of the maximum number of parts upstream of the BN to the number of the upstream resources. The lower the ratio is, the closer to tense flow. Conversely, the larger the ratio is, the higher the protective inventory.

Before the occurrence of the BN, protective capacity was implemented as an addition to the existing capacity, which ranged from 0 to 16%. All runs lasted 500 hours, with a 40-hour warmup period, and each experiment was replicated five times (Orue et al., 2021).

4.3.2 Simulation model assumptions

To maintain simplicity and to avoid a loss of generality, the process times were modelled as random uniform distributions. Specifically, for every process *p*, the average capacity C_p (in parts per hour) and variability V_p of that capacity was assumed. Thus, the processing time for a component followed a random distribution in the following interval:

$$[\frac{60}{C_P} \times (1 - V_p), \frac{60}{C_P} \times (1 + V_p)].$$

The BN capacity, which was 100 parts/hour, had no variability, and different capacities for the non-BN were analysed. Demand was modelled as long batches (150 or 250). For each batch, different process times were assumed for each process given by a value of the capacity Cp of the corresponding process (the processing time for each part of the batch is calculated as described above).

Additional sources of the unavailability of processing capacity resulting from breakdowns and repair times were also analysed. The time between failures and the time for repairs followed an exponential distribution. The mean time between failures

(MTBF) was 100 minutes, and the mean time to repair (MTTR) was calculated so that the total unavailable time attributed to repairs was 0.5%.

4.3.3 Experimental design and performance measures

The experimentation consists of measuring the percentage of starvation at the BN. This percentage is calculated as the time during which the BN has been stopped because no material has arrived from previous processes with respect to the total available time.

To carry out the experiment, all the factors in Table 10 were combined. The two levels of production batches were combined with the six levels of protective inventory and the nine levels of protective capacity. The results obtained after the experimentation are presented in Table 10.

Table 10. Summary of experimental factors

Experimental factor	Level
Lot size to be manufactured	Low: 150; high: 250.
Protective inventory	Six levels from tight flow to high protection. Protective inventory (%): 0, 33, 100, 200, 300 and 400.
Protective capacity percentage	Nine levels from low to high protection. Protective capacity (%): 0, 2, 4, 6, 8, 10, 12, 14, and 16.
Variability	12%
MTBF	100
Unavailability	0.5%

4.3.4 Case study 2 results

The general results are illustrated in Figure 22, which shows the relationship between protective capacity and protective inventory in relation to BN starvation. The points in the figure represent the average of the five replicate experiments. To determine the existing values around the sample mean of the replicate experiments, Figure 23 shows the confidence intervals for each factor experimented with a confidence level of 95%.

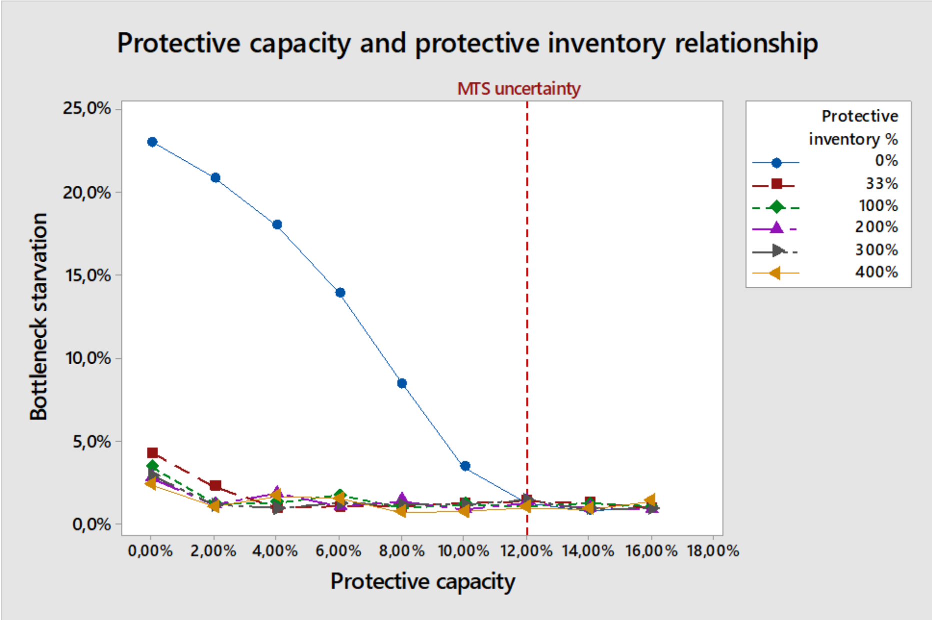

Figure 22. Relationship between protective capacity and protective inventory (powered by Minitab software)

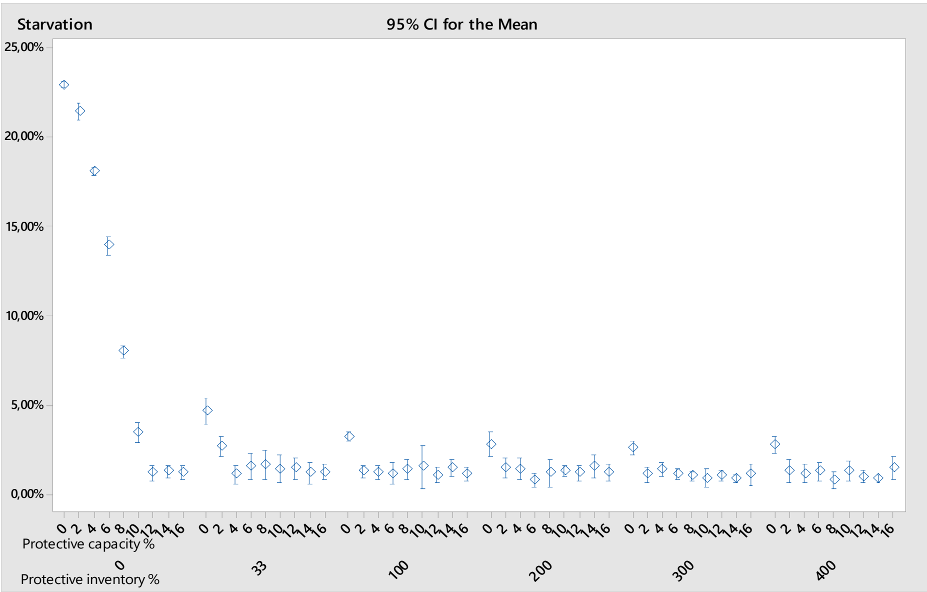

Figure 23. Confidence intervals with a 95% confidence level (powered by Minitab software)

To assess the significance of the defined experimental factors, ANOVA was performed. To determine the possibility of a significant difference in the means of the above factors, Tukey's pairwise comparison post hoc test was performed. The significance level was set to 5%.

4.3.4.1 Protective inventory analysis:

Table 11 shows the results of the ANOVA performed on the starvation percentage with respect to the protective inventory levels. Figure 24 shows the results of Tukey's comparison test. It can be concluded that the lowest level of protective inventory has a significant effect on BN starvation if the protective capacity is below system variability (12%). An increase in the protective inventory level would improve material starvation in the BN but only to a certain level. Above a certain level of protective inventory, there is no improvement. If protective capacity is equal to or greater than system variability (12%), then protective inventory has no effect on BN starvation.

Table 11. ANOVA results regarding protective inventory.

ANOVA (significance level α = 0.05)	DF	Adj SS	Adj MS	*F*-value	*p*-value
Protective inventory %	5	0.2829	0.056578	43.80	0.000
Error	264	0.3411	0.001292		
Total	269	0.6239			

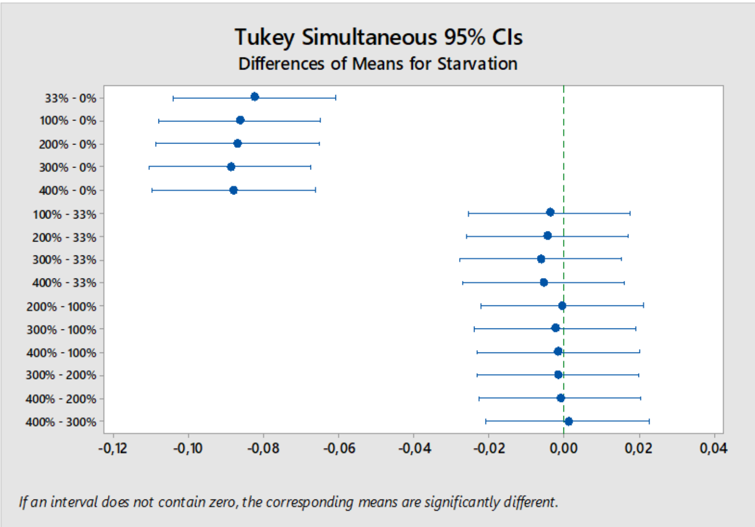

Figure 24. Tukey´s comparison test of protective inventory (powered by Minitab software)

4.3.4.2 Protective capacity analysis:

Table 12 shows the results of the ANOVA performed on the starvation percentage with respect to the protective capacity levels, and Figure 25 shows the results of Tukey's test.

The comparison of the lowest and highest protection levels indicated that protective capacity was only one significant factor in BN starvation. Furthermore, the lowest protective inventory levels and a higher protective capacity resulted in lower BN starvation. As the protective inventory increases, protective capacity becomes less important.

Table 12. ANOVA results regarding protective capacity.

ANOVA (significance level α = 0.05)	DF	Adj SS	Adj MS	*F*-value	*p*-value
Protective capacity %	8	0.08647	0.010808	5.25	0.000
Error	261	0.53747	0.002059		
Total	269	0.62394			

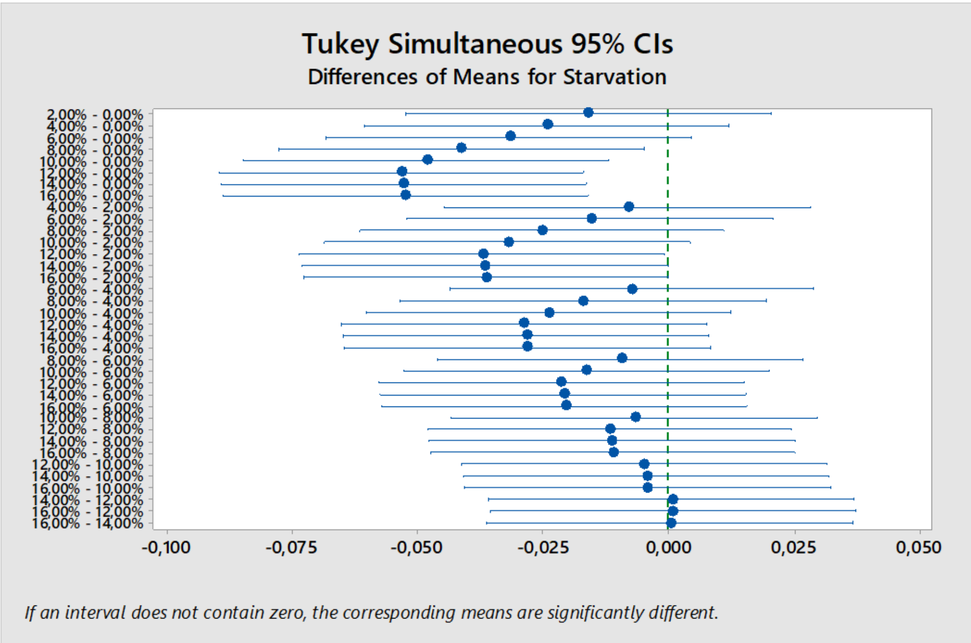

Figure 25. Tukey's comparison test of protective capacity (powered by Minitab software)

4.3.5 Case study contributions

According to the literature, protective capacity and protective inventory are key factors in the implementation of step three of the TOC–DBR. To continue designing a systematic implementation process for system subordination to the BN, it was important to understand the relationships among the factors in different environments. CS2 has presented an analysis of an MTS environment, in which system variability was lower than that of MTO environments.

The results show that the lowest level of protective inventory is a relevant factor in BN starvation if protective capacity is below system variability. If protective capacity is equal to or higher than system variability (12%), protective inventory does not affect BN starvation (Orue et al., 2021).

Environments with relatively low variability and objectives of achieving low costs (high efficiencies) with short lead times are characterised by low protective capacity. Thus, protective inventory is needed to absorb system fluctuations. With the retention of sufficient protective inventory, low levels of protective capacity can be maintained (Orue et al., 2021).

From this conclusion, the contribution of CS2 can be drawn:

`In MTS environments, protective inventory plays a key role in system performance.`

However, this contribution clashes with the contributions of other authors. Some studies refer to the notion that protective capacity is an important factor in relation to protective inventory. As Krajewski et al. (1987) comments in his paper, Japanese managers used protective capacity instead of protective inventory years ago to protect the output of a system. In addition, to generate inventory to protect the BN (protective inventory), it is necessary to have a capacity margin in the non-BN resources (protective capacity).

Other authors, such as Atwater & Chakravorty (1994), provide two significant findings in their research for operations managers. On the one hand, the authors validate the use of protective capacity as a viable means of achieving faster cycle times while operating with lower inventory levels. On the other hand, they conclude that lines with protective capacity require less inventory in the system to achieve relatively stable cycle times. Following the same line of argument, according to research by Hurley & Whybark (1999), it appears that protective capacity, when used, can reduce freight inventories at non-BN stations. The results of the Hurley & Whybark´s simulation study indicate that the use of variance reduction programmes or protective capacity are effective techniques for buffering against uncertainties in manufacturing. Indeed, these techniques seem to be preferred alternatives to the traditional use of WIP protective inventory for increasing the output rate of the production cell.

Taking into account the results obtained in CS2 and the contributions of the aforementioned authors, doubts arise about the role of the protective capacity factor in different environments. For this reason, CS3 is proposed to analyse the behaviour of protective capacity in different environments of variability. The protective capacity factor will be analysed in MTS and MTO environments and in the latter, from RBC to VMC environments.

4.4 Case study 3

4.4.1 Simulation model based on case study 1

As in CS2, a simulation was designed based on CS1, where the systematic process of implementing the first two steps of the TOC-DBR methodology was executed. However, in CS3, the focus was analysing the impact of protective capacity in different manufacturing environments. The first step involved strategically identifying the BN resource, which was determined to be the fourth resource in this case. Following the selection of the BN, the second step involved deciding how to exploit the system's limitations. In CS1, it was decided to schedule the BN at 80% of its capacity due to the challenges in accurately defining the processing time. Once the scheduling rules were established, the objective was set to meet the BN schedule above 99%. This objective was aimed at ensuring a stable system and achieving the defined operational performance.

The system being analysed in this study is a flow-shop workshop that consists of six workstations. In this system, all parts undergo processing at each workstation and follow the same route throughout the production process. To simulate the behaviour of the system in different environments, the DBR model shown in Figure 21 was employed.

4.4.2 Simulation model assumptions

As previously discussed in section 2.2, Characteristics of companies with MTO environments companies, the MTS, RBC and VMC features vary in terms of product variability and order size. In practical terms, this variation implies that processing times become less predictable when transitioning from MTS to VMC (with RBC falls somewhere between MTS and VMC).

Consequently, to assess the impact of protective capacity in different environments (MTS, RBC and VMC), these environments have been simulated by considering the variability in process durations for operations other than the BN resource.

In all environments, regardless of their type, it is assumed that the capacity of the BN resource remains constant at 100 parts per hour. Additionally, this specific process is assumed to have no variability as any anticipated variability has already been considered during the scheduling process, where the BN is scheduled at 80% of its capacity. Moreover, for the purpose of the analysis, it is assumed that there are no breakdowns or disruptions in the operation of the BN.

Process times are modelled as random uniform distributions. In particular, for every process p, we assume the average capacity C_p (in parts per hour) and variability V_p of this capacity so that the time to process a part follows a random distribution in the following interval: $[\frac{60}{C_P} \times (1 - V_p), \frac{60}{C_P} \times (1 + V_p)]$.

In terms of the protective capacity of the system, the capacity for processes other than the BN resource may vary in increments of 10. Note that these values should be larger than 100, such as 110, 120, etc. The purpose of the protective capacity is to ensure that the capacity exceeds 100 for non-BN processes. It is assumed that the capacity for all non-BN processes is the same

In terms of protective inventory, the baseline scenario is to keep the minimum inventory in the system. Therefore, the number of parts before the BN will be equal to the number of parts that these processes can process at any given time without additional inventory. Any amount above this value represents additional inventory that can compensate for system variability and contribute to increasing the utilisation rate of the BN resource. However, in MTO environments, this additional inventory is not usable as it is not known in advance what products will be produced.

In the model, we considered the presence of breakdowns and repair times as additional factors affecting the availability of processing capacity in all environments. Both the MTBF and MTTR were modelled using exponential distributions. The MTBF was set to 100 minutes, while the MTTR was calculated to ensure that the total downtime due to repair time accounted for 0.5% of the overall time.

Transfer times and setup times are not explicitly modelled in the simulation. Instead, they are implicitly considered as part of the overall capacity and variability of the processes.

4.4.3 Experimental design and performance measures

The experimentation phase involves measuring the required protective capacity on non-BN resources to achieve a BN utilisation rate exceeding 99% but not exceeding 99.4%. The protective capacity is assumed to be a multiple of 10, with a minimum of 0% (10%, 20%, etc.).

To conduct the experiment, various experimental factors, as outlined in Table 13, are considered. By combining all the factors and their corresponding levels, the necessary values of protective capacity to ensure that the BN operates above 99% are collected.

Minimizing the protective inventory is crucial, as the objective is to prevent the inventory from absorbing the system's variability.

Table 13. Summary of experimental factors

Experimental factor	Level
Lot size to be manufactured	Low: 150; high: 250
Protective inventory	Minimum
System variability	Ten scenarios for process variability Process variability (%): 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50
MTBF	100
Unavailability	0.5%

4.4.4 Case study 3 results

The analysis of the experimental results involved two different methods. Figure 26 illustrates the relationship between protective capacity and system variability. The levels of protective capacity were determined based on the arithmetic mean of BN starvation. Using five experimental replications, the protective capacity levels were adjusted to ensure that the average starvation in the BN remained below 1%. This approach guarantees that the BN programme is fulfilled at a rate exceeding 99%.

Figure 27 also depicts the relationship between protective capacity and environmental variability, but the results were obtained using a different approach. It was defined that starvation should fall between 0.6% and 1% to ensure compliance with the BN schedule, and all levels of protective capacity that met this requirement were identified. Subsequently, the arithmetic mean was calculated based on these levels.

Figure 28 presents the confidence intervals for each tested factor, with a confidence level of 95%.

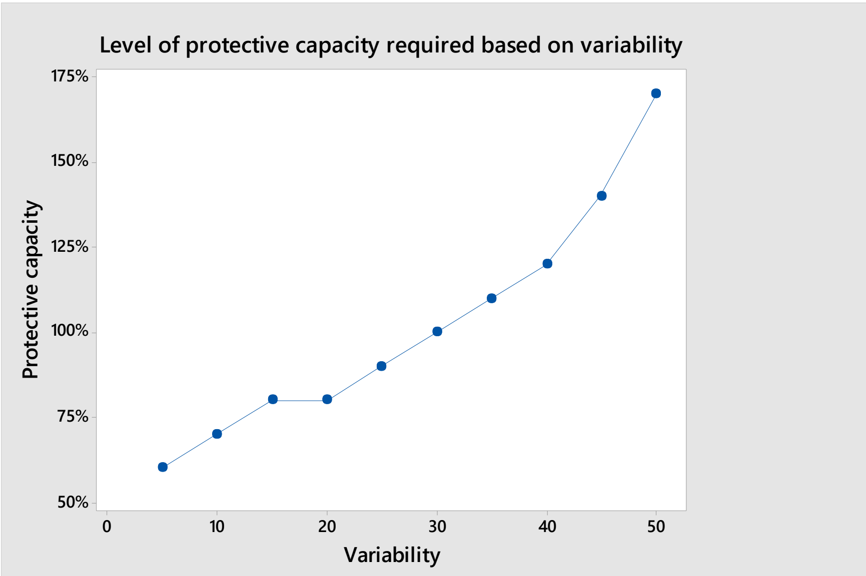

Figure 26. Relationship between protective capacity and variability (powered by Minitab software) (Orue et al., 2022, p. 8)

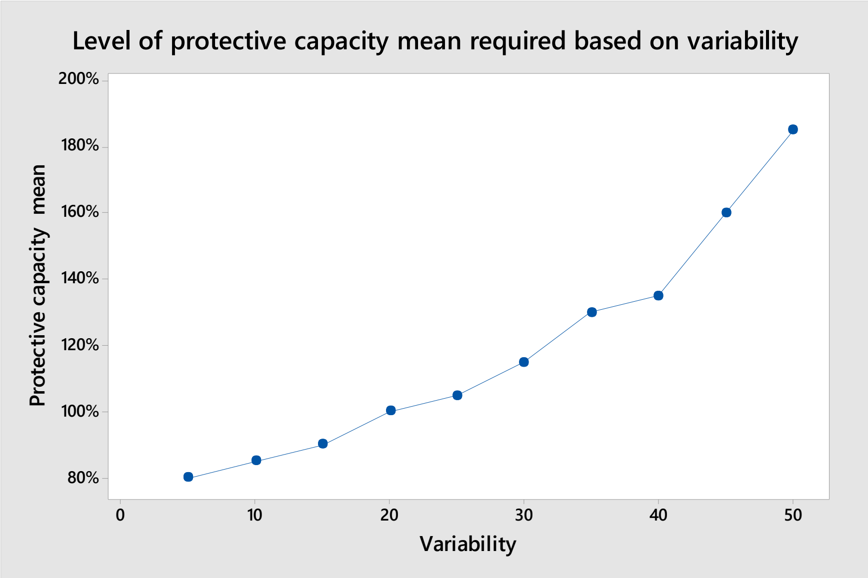

Figure 27. Relationship between protective capacity and variability (powered by Minitab software) (Orue et al., 2022, p. 9)

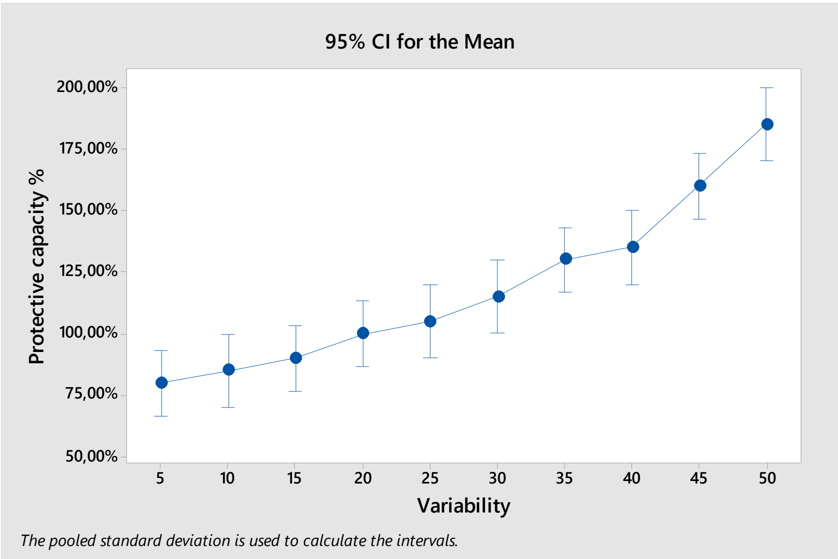

Figure 28. Confidence intervals with a 95% confidence level (powered by Minitab software) (Orue et al., 2022, p. 9)

4.4.5 Case study contributions

Analysis of the results reveals that the definition of the level of protective capacity in MTO environments has direct implications for the implementation of step three of the TOC-DBR methodology.

MTO environments are characterised by higher levels of variability and unpredictability compared to MTS environments. This increased variability necessitates higher levels of protection for the BN resource against system variability. Within the MTO environment, there are two distinct types of companies: RBCs and VMCs. VMC environments, which involve fully customised products with minimal or no repetition, exhibit the highest level of variability. In such environments, the concept of a protective inventory becomes ineffective due to the lack of advance knowledge about customer orders. With limited unit orders and uncertainty about customer demands, it is not feasible to maintain sufficient inventory to absorb system variability. In RBCs, although the variability is lower than in VMCs, the importance of protective capacity remains significant. Despite reduced variability, the level of customisation and small batch sizes make it impractical to produce inventory in advance. Thus, protective capacity becomes crucial for managing and absorbing variability in the system. The distinction between protective capacity and protective inventory highlights the different approaches required to address variability in MTO environments. While protective inventory may not be applicable in highly customised environments, protective capacity assumes greater importance in ensuring system stability and performance. These observations align with the findings of Orue et al. (2022), emphasising the significance of protective capacity in MTO environments, particularly in RBCs and VMCs.

In conclusion, determining the appropriate level of protective capacity is a critical strategic factor in implementing Step three of the TOC-DBR methodology. Managers in MTO environments need to recognise the indispensability of protection against variability to achieve the desired BN schedule and maintain system stability. It is important to understand that pursuing efficiency in non-BN resources, which serve to protect against variability, can lead to insufficient protective capacity and result in BN starvation. Hence, it is advisable to hedge and fine-tune the level of protection until an optimal level of protection is achieved (Orue et al., 2022).

Authors such as Bessant (1998) define that key factors, such as protective capacity in this case, should be aligned with continuous improvement activities. To achieve this alignment, it is necessary to measure and monitor these key factors via monitoring processes.

To accomplish this continuous improvement objective, it is advisable to monitor the consumption of protective capacity and adjust the level of protection to ensure that the system remains stable over time. This will ensure the expected system performance (Orue et al., 2022).

Taking into account the above findings, the two contributions of CS3 are presented as follows:

`The validation of protective capacity required is a strategic decision for the organisation.`

´There is a need to manage and monitor the use of protective capacity.`

From both the contributions of CS1 and CS3, it can be concluded that the definition of the level of protective capability is a strategic decision for the organisation. For this reason, when designing the implementation process of the third step of the TOC-DBR methodology in MTO environments, this strategic decision and its management should be taken into account (Orue et al., 2022).

In the case of the TOC-DBR methodology, it is an operational model that is aimed at addressing system variations using an implementation and feedback system via continuous improvement (Cox & Schleier, 2010). However, being an operational model, the methodology lacks the systematic integration of the organisation's strategic vision.

In industrial companies, the S&OP process is often used to link the tactical, strategic part with the operational part (Feng et al., 2008).

The S&OP process usually produces plans that connect the company's strategic objectives with the production plan to effectively match supply (or capacity) with market demand (Feng et al., 2008). Thus, S&OP is aimed at efficiently using production capacity to effectively respond to market demand in terms of cost, time and quality (Lahloua et al., 2018).

To further analyse the S&OP process, it is necessary to carry out a literature review in the field of the S&OP process. For this reason, a specific literature review in S&OP is conducted in the introduction of CS4. Once the literature review is conducted, the aim is to integrate the inputs via an investigation of CS4 to design the final systematic process.

4.5 Case study 4

4.5.1 Specific literature review, sales and operation process

Traditionally, the four main functions of a supply chain (procurement, production, distribution and sales) have been separately managed and connected by inventory (Pereira et al., 2020). This approach simplifies management but disregards the interdependence of the functional areas. In some cases, individual plans can lead to incompatible decisions when integrated, which is why S&OP emerged as a solution to this problem (Pereira et al., 2020). The term originally derived from Manufacturing Resource Planning literature as a substitute for Aggregate Production Planning (Singhal & Singhal, 2007). The concept has evolved to encompass two complementary plans: a production plan and a sales plan based on demand (Olhager et al., 2001). More recently, researchers have started to view S&OP as a fully integrated supply chain planning that simultaneously considers all functions (Feng et al., 2009). The effort required for cross-functional collaboration is justified by the evidence that it can improve organisational performance and maximise its global value (Feng et al., 2008, 2009; Thomé et al., 2012). The value of integration depends on the specific supply chain, such as coordinating marketing and production decisions to shape demand in environments with limited capacity. The value of integration depends on the specific supply chain, such as coordinating marketing and production decisions to shape demand in environments with limited capacity (Gilbert, 2000).

The S&OP process is a crucial aspect of business operations that involves developing a plan to meet anticipated demand (Olhager et al., 2001). The process encompasses all steps necessary to establish a tactical-level production plan that aligns the company's strategic objectives with the operational elements of the production master plan to effectively balance supply and demand (Feng et al., 2008). Deviation between sales plans and production plans will be reconciled in different ways depending on the production approach. Thus, the mechanism to compensate for deviations in MTS companies is stock, while in the case of MTO firms, a backlog plan is required (Apaolaza et al., 2022).

The end goal of S&OP is to make the most efficient use of production capacity and respond to market demand in terms of cost, time and quality. In today's globalised, uncertain and complex supply chain environment, integrated planning is becoming increasingly important (Tuomikangas & Kaipia, 2014). In uncertain international supply chain environments, such as MTO environments, production management is important to ensure stability and visibility (Lahloua et al., 2018).

The length of the planning horizon and the significance of decisions determine the different planning levels (Kilger & Stadtler, 2008).

- Strategic planning (long-term): This type of planning involves decision-making that will shape the future of the supply chain or company. These decisions focus on designing the supply chain for the long term, covering several years.
- Tactical planning (mid-term): This level of planning creates a preliminary plan for regular operations and is usually performed at an aggregate level. It involves estimating rough quantities and schedules for the resources and flows. The planning horizon ranges from several months to one year.
- Operational planning (short-term): This level of planning focuses on providing detailed instructions for immediate implementation and control. It requires a high level of detail and has a planning horizon of several days to a few weeks.

As a part of S&OP processes, the DDAE model arose in response to the VUCA environment to provide a complete model for management (Ptak & Smith, 2018).

4.5.1.1 DDAE Model

The DDAE model is a recently developed model that emerged in the VUCA context with the aim of providing a comprehensive response to the current needs of organisations. The model consists of three components that jointly cover the operational, tactical and strategic management levels, namely, the demand-driven operating model (DDOM), demand-driven S&OP and adaptive S&OP (Figure 29). The DDAE approach seeks to coherently address all three management levels through cycles of configuration, feedback, and reconciliation. Relevant ranges for management and relevant information are crucial for the model (Ptak & Smith, 2018).

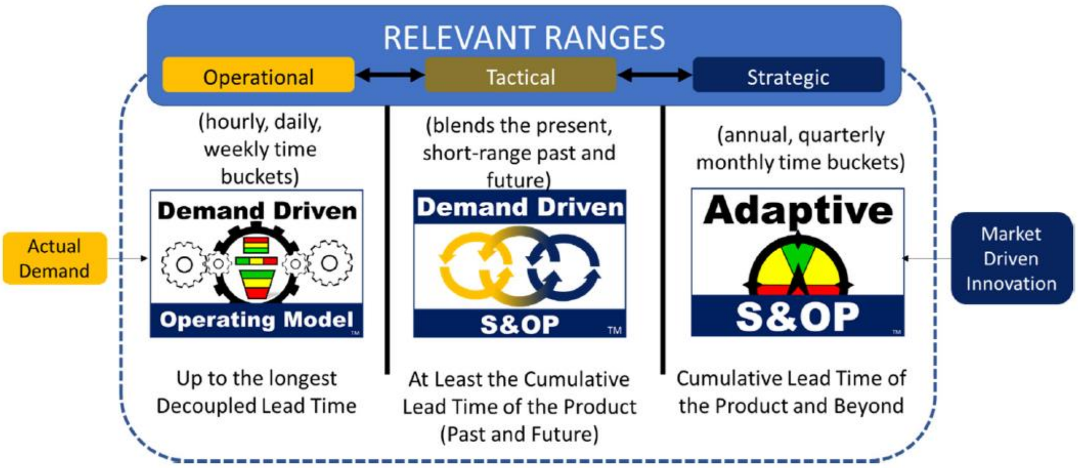

Figure 29. DDAE model and definitions of relevant ranges (Figure 7-1, p. 156)

Ptak and Smith (2018) define four prerequisites for relevant information, emphasising that all of them are necessary for this purpose: understanding relevant ranges, tactical reconciliation among relevant ranges, a flow-based operating model and a set of flow-based metrics. These prerequisites are briefly described below:

- Understanding relevant ranges means that assumptions are valid within appropriate periods. Consequently, the assumptions and relevant information related to different ranges can significantly vary, which is the case for the operational, tactical and strategic ranges.
- Relevant ranges need to be continuously and iteratively reconciled. When addressing strategy, a company must consider its operational capability and performance. Similarly, strategy influences operational capability. To reconcile the operational and strategic ranges, the tactical range must function in a bidirectional manner.
- A flow-based operating model is aimed at protecting and promoting flow. From this perspective, flow can be a unifying factor that extends beyond operations to different functions.
- To support a flow-based operating model, a company should adopt appropriate metrics for each of the relevant ranges. These metrics should be reconcilable across ranges.

In this way, these metrics should help the company maintain organisational coherence and control variability. In the context of DDAE, the work performed by people who are coherently aligned is referred to as collaboration (Ptak & Smith, 2018). The DDAE model adopts the following definition for S&OP, which is a key process within its framework (Pittman & Atwater, 2016, p. 154):

'A process to develop tactical plans that provide management the ability to strategically direct its businesses in continuously achieving a competitive advantage by integrating customer-focused marketing plans for new and existing products with the management of the supply chain. The process combines all the plans for the business (sales, marketing, development, manufacturing, sourcing and financial) into one integrated set of plans. The process is performed at least once a month and reviewed by management at an aggregate (product family) level'.

The DDOM effectively links the actual demand and S&OP, the tactical range of the DDAE model (Ptak & Smith, 2018); That is, it matches the operational capability and the strategic requirement. Thus, it generates real-time signals based on the actual demand. The DDOM strongly depends on demand-driven MRP (DDMRP), "a method to model, plan and manage supply chains to protect and promote the flow of relevant information and materials. DDMRP is the supply order generation and management engine of a demand-driven operating model" (Ptak & Smith, 2016). The three components of the DDOM are DDMRP, demand-driven scheduling, and demand-driven execution (Ptak & Smith, 2016) .

The model defines a five-stage implementation road map to guide companies through the progressive adoption process (Figure 30). The key aspects of each stage are summarised below:

- Stage 1 is usually the starting point for most companies. In this context, the management approach to maximise overall results focuses primarily on minimising costs and maximising resource utilisation. The concept of flow is disregarded.

- Stage 2 is the first step towards becoming a demand-driven company. The goal is to improve overall performance. The main operational driver is flow oriented towards improvement. The concepts, criteria and metrics of the second phase are not compatible with those of the first phase. Therefore, transitioning to the second phase involves a change in methodology, which implies a change in mindset.
- Stage 3 is the first step towards a demand-driven organisation. It requires the full implementation of DDOM and focuses on improving flow performance via tactical analysis that begins with S&OP.
- The objective of Stage 4 is to enhance DDOM capability throughout the organisation and the market. Therefore, the entire organisation must understand it from a global perspective.
- Stage 5 is concerned with adapting and improving the organisational capabilities of the organisation by facilitating flow among the participants in the supply chain.

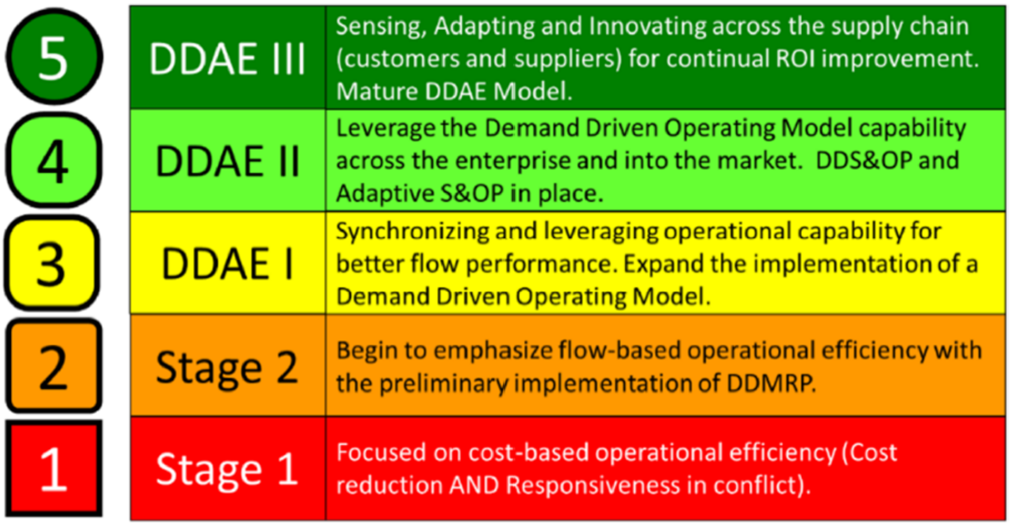

Figure 30. DDAE development path (*Demand Driven Institute*)

The DDAE model integrates an interesting concept known as the capacity buffer that protects the control points and decoupling points from system variability. The capacity buffer can be defined as the protective capacity that provides agility and flexibility for upstream resources to match system variability and helps manage this protective capacity (Ptak & Smith, 2018, p. 72).

4.5.1.2 Results of specific literature review

From the specific literature review, it can be concluded that the S&OP process is a valid tool for aligning the operational part with the tactical and strategic part. Specifically, as part of this S&OP process, there is a complete management model named DDAE, which is designed to respond to VUCA environments such as the MTO environment. In addition, as part of this complete management model, there is a concept of capacity buffer that serves to monitor and manage the protective capacity of a system.

Furthermore, authors such as Orue et al. (2023) suggest the integration of the three levels of management - operational, tactical and strategic - in the process of implementing the TOC-DBR methodology.

Therefore, the following section is aimed at integrating all these concepts into the systematic process of applying the third step of the TOC-DBR methodology for MTO environments in CS4. The section intends to enrich the systematic process resulting from CS1 via the integration of the DDAE model obtained through the contributions of CS1, CS2 and CS3.

4.5.2 Introduction to the company

The company in question specialises in tube manufacturing and is located in the Basque Country, Spain. Their workshop consists of various areas, including tube pressing and extrusion, tube straightening, stabilisation ovens, surface cleaning, and X-ray testing. The company primarily produces customised products in small and medium-sized quantities, which has not always been the case. Until a few years ago, the company produced large volumes of a few types of tubes for customers who were stockists. Due to the large inventory, the company were able to respond to the market with exceptional service levels. However, a radical market shift in which end customers (such as extraction companies and refineries) replaced the stockists occurred, forcing the company to change its strategy and transition from an MTS environment to an MTO environment. In the new arrangement, the end customers buy directly from them, and the orders consist of various types of tubes with a small number of units per type. Figure 31 depicts the material flow in CS4.

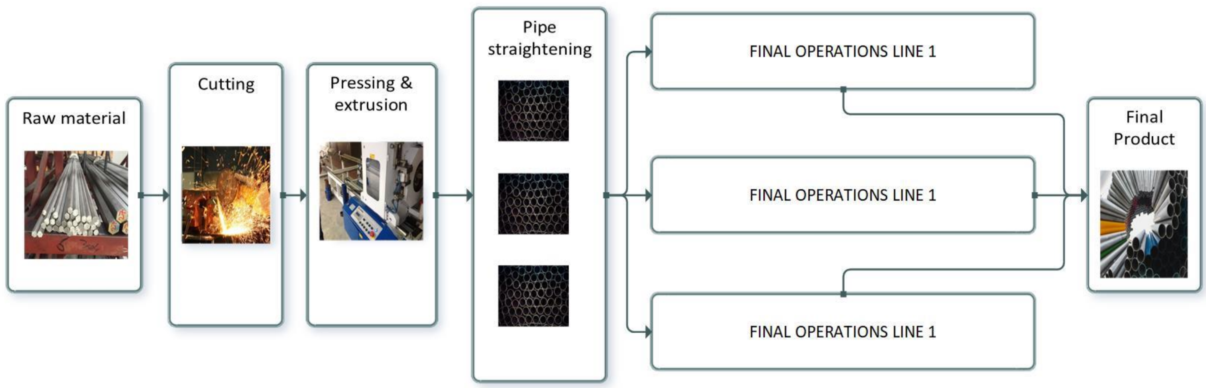

Figure 31. General material flow for CS4. Note: based on Lizarralde et al. (2019)

4.5.3 Drum-buffer-rope implementation

Lizarralde et al. (2019) found that all the areas in the workshop released production orders as soon as possible, regardless of their priority or the availability of sufficient materials to support the workload in all areas, because the focus was maximising production. Additionally, the balance of orders released in the three manufacturing routes after the BN was not taken into account. The result was an excessive inventory that was difficult to control, long lead times and low service levels.

To solve this problem, the systematic implementation process for the first two steps was applied (Lizarralde et al., 2019).

First, a load/capacity study was conducted within a specific time frame to compare the available capacity of each resource with the capacity utilised by demand. It was not a straightforward task since the customisation of the product made it difficult to determine the real load and capacity, as the processing times were challenging to accurately estimate.

The analysis revealed that the pressing and extrusion section had the highest load/capacity ratio, followed by the three subsequent routes where occasional capacity problems were also observed.

The second step was the strategic selection of the BN. In this case, it was decided that the company's BN would be the pressing and extrusion section since it was a shared resource for 100% of the products, and its load remained stable over time. Additionally, it was a resource that required critical knowledge for the organisation.

Last, scheduling policies were defined to exploit the system, specifically, policies regarding when to plan the use of the BN and the subordination of the remainder of the system.

The model of the solution that was designed for this case is shown in Figure 32.

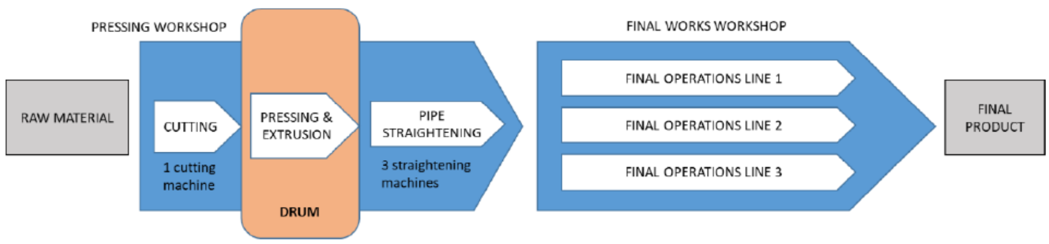

Figure 32. TOC design model (Lizarralde, 2020, p. 101)

The most relevant results obtained after the DBR implementation, including the systematic process of the first two TOC steps, are presented as follows: (1) service level increased from 35% to 85%, (2) manufacturing maturity period decreased by 37% and (3) inventory level (WIP) decreased by 30% (Lizarralde et al., 2019).

4.5.4 Theory of constraints – drum-buffer-rope step three analysis

Data collection and analysis were carried out through semi-structured interviews with four company managers and the staff member who led the implementation process.

Their answers revealed that the defined policies were focused on local optimisation of specific areas rather than global optimisation. Additionally, another crucial aspect in planning was that other non-BN resources after the BN were not taken into account. Although they were not capacity-constraining in aggregate, they could still encounter occasional issues in meeting the schedule if it included load spikes. Due to these load spikes, the three routes following the BN were unable to process more than a certain quantity of units per week for specific product variants.

After analysing the root cause of the problem, two decisions were made to promote optimal system performance. The first decision was to increase the protective capacity of non-BN resources after the BN by 15%. This increase was aimed at ensuring enough capacity to produce orders on time. The second decision was to define decision rules to control incoming orders in the system, allowing for timely scheduling and manufacturing of production orders.

4.5.5 Case study 4 results

The results from the CS were analysed, and a systematic process for implementing the third step of TOC–DBR in MTO environments was refined (Figure 33).

To design the systematic process, the specific literature review of section 4.5.1 has been taken into account. The requirement that the systematic process must ensure that the designed system remains stable over time, guaranteeing its operational performance, was also considered. To ensure this operational performance, the strategic factor of protective capacity must be managed, as demonstrated in the results of CS3. Additionally, the systematic process should integrate continuous improvement tools to detect and resolve potential issues within the system.

Considering the conditions that the systematic process must fulfil, it has been defined that the process consists of three management levels. According to the specific literature review related to the DDAE approach developed in section 4.5.1., these three levels are operational, tactical, and strategic. The DDAE approach is aimed at coherently addressing all three levels through continuous improvement cycles of configuration, feeding and reconciliation (Ptak & Smith, 2018). Accordingly, the developed systematic process was divided into three phases – model configuration, operating model and tactical S&OP – which are explained below.

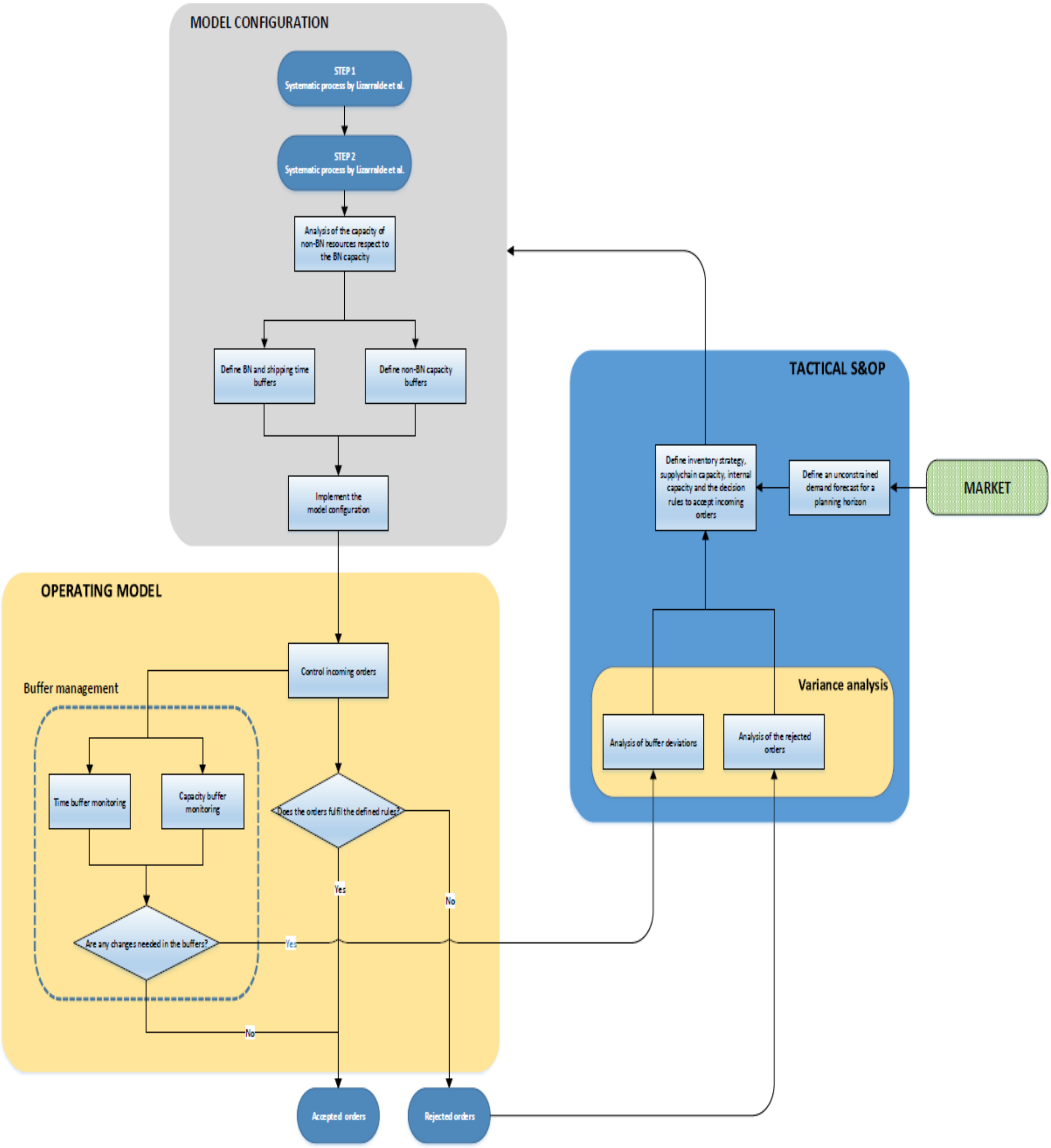

Figure 33. Systematic process for step three of the TOC methodology (Orue et al., 2023, p. 210)

- Model configuration phase:

The configuration phase of the model refers to the steps to be followed in designing a solution for the implementation of the third step of the TOC-DBR methodology. Once the first two steps of the systematic process developed by Lizarralde et al. (2020) have been implemented, the next step is to analyse the capacity of the non-BN resources and compare it with the BN capacity. The capacity of each non-BN resource must first be calculated.

Next, the time buffers for the BN and shipping as well as the capacity buffer for the non-BN resources need to be defined. For the time buffers, the necessary size must be determined to prevent starvation at the BN and ensure that orders arrive on time. It is recommended to generate order families, taking into account the routes that each order follows before and after the BN. For the capacity buffer, a similar action must be taken, defining the level of protective capacity required in the non-BN resources to prevent starvation at the BN (Orue et al., 2023).

The third and final step of this first phase is the implementation of the designed TOC-DBR solution. Figure 34 shows the resulting design from the configuration phase of the model.

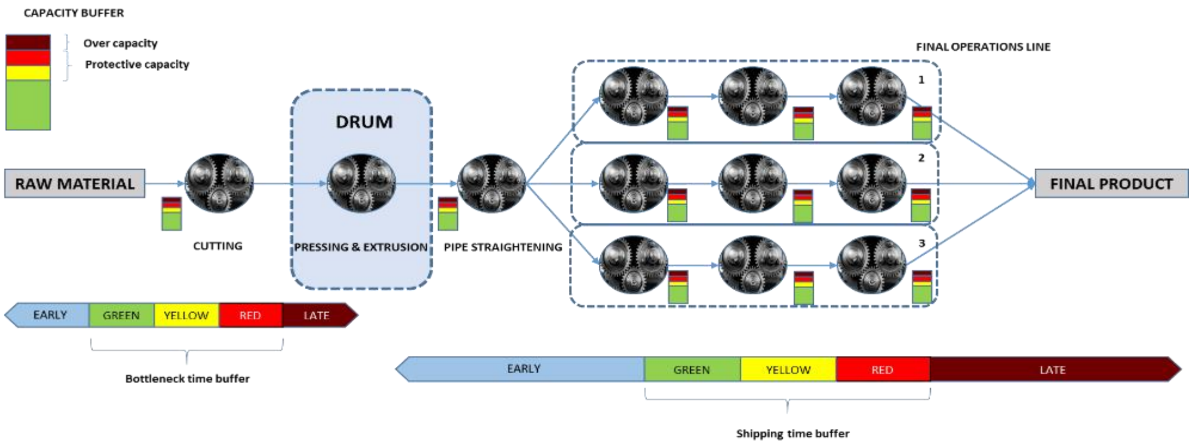

Figure 34. CS's third-step solution design (Orue et al., 2023, p. 211)

- Operating model phase:

Once the solution design has been implemented, we proceed to the operational model phase. This phase lasts from a few days to a few weeks, depending on the type of company and the environment (Pereira et al., 2020); that is, the planning period for the operational part needs to be defined.

The first step in this phase is controlling the entry of orders, which involves defining rules or conditions for their acceptance. The rules refer to the type of work that should enter the system to keep it stable. The rules may include, for example, the percentage of orders that must pass through the BN and the specific weight of non-BN work in relation to the BN. Once the rules are defined and the incoming orders are controlled, the path splits into two.

On the first path, the goal is to determine whether the incoming orders meet the defined acceptance criteria. If the answer is negative, the order is rejected. If the answer is affirmative, the next steps will be accepting the order and scheduling and manufacturing it.

The second path requires monitoring the BN buffer, shipping time buffer, and capacity buffer. For this monitoring, the intuitive method of the traffic signal is applied. This method involves dividing the buffer into green, yellow, and red zones and is applied in the demand-driven adaptive business model. This method serves as a tool for continuous improvement of the system, as it allows improvement in the buffer size by observing and analysing how much is consumed in each zone (Orue et al., 2022; Orue et al., 2023).

- Tactical S&OP phase:

In this last phase, steps are defined to link the organisation's strategic plans with the execution phase.

In the systematic process of implementing the third step of TOC-DBR, it is necessary to consider both the strategic aspects of the sales plan and the operational phase. Based on the continuous improvement process of the DDAE model, the deviation in the buffers and rejected orders should be analysed. Taking into account the projection of future demand, a strategy that aligns with inventory, the supply chain, internal capacity, and decision rules for accepting production orders needs to be defined.

If any changes occur, it is necessary to return to the configuration phase of the model and reanalyse the BN and redefine the buffer levels.

4.5.6 Case study contributions

Managing production plants that operate in MTO environments is challenging due to the variability of the market, which means that demand cannot be accurately predicted.

In this CS4, the third step has been further developed and an evolution of the systematic process has been designed to implement the third step of the TOC-DBR methodology (Orue et al., 2023).

The three main contributions of CS4 focus on the MTO environment. The first contribution is the

`Final version of the systematic implementation process of the third step of the TOC-DBR methodology`.

The second contribution is

`Introduction of the capacity buffer concept of the demand-driven adaptive business model into the TOC-DBR methodology`.

The last contribution is

´To propose how an organisation can integrate the S&OP process into the TOC-DBR methodology via the DDAE methodology´.

Chapter 5

5 Discussion

Chapter 4 describes the work carried out by the researcher to obtain appropriate answers to the RQs. The primary purpose of this chapter is to showcase the attainment of the research objectives through clear and appropriate responses to the questions posed. The chapter encompasses a thorough analysis of the findings derived from the four CSs.

5.1 Answers to the research questions

In this section, the ultimate response to each RQ is provided and substantiated through various methods, including a literature review and comprehensive CS analysis. The RQs, which were introduced and interconnected in Chapter 3, are addressed. The primary RQ, as originally formulated, is presented as follows:

RQ1. How can non-BN resources of a production system in an MTO context be managed both systematically and by means of TOC-DBR to enhance performance?

However, after conducting a systematic literature review and throughout the execution of the different cases and the development of the systematic process, two new questions emerged. Both sub-questions are related to the implementation of the third step of the methodology and are presented as follows:

- RQ1a. How should the level of protective capacity of non-BN resources be defined?
- RQ1b. How can the protective capacity be managed?

5.1.1 Answer to research question1

In the theoretical framework, no article has investigated the systematisation of the third step of the TOC-DBR methodology. As Pretorius (2014) mentions, there is a lack of clarity regarding the decisions that allow moving to the next or previous step in the TOC-DBR methodology. Ikeziri et al. (2018, p. 26) concluded that POOGI (i.e. how to apply Goldratt's five steps) "needs more theoretical studies that discuss and evaluate TOC as a structured process of continuous improvement".

Furthermore, regarding the future direction of his thesis, Lizarralde (2020) stated that expanding the research to include an investigation of the third step of the POOGI would be very beneficial, as all three steps play a crucial role in optimising the performance of the current system. To improve the theoretical development of PPCS MTO contexts, it is important to gain a deeper understanding of how the remaining resources of a company can be effectively aligned with the BN programme. This knowledge will significantly contribute to enriching the theoretical framework in this field.

Considering the above findings, the need to design a systematic process to apply step three of the TOC-DBR methodology is clear.

Chapter 4, Field Work, encompasses a comprehensive analysis of the field work conducted by the researchers to address RQ1, as well as the systematic process constructed during the research project through real and simulated CS. This systematic process and its application in the field work yielded the answer to RQ1. To understand RQ1 in detail, the explanation has been divided into two parts as follows:

5.1.1.1 Answer to the first part of RQ1

How can non-BN resources of a production system in an MTO context be managed both systematically and by means of TOC-DBR […]

The designed systematic process is based on Lizarralde's (2020) work and complements it by adding the systematisation of the third step. This systematic process has been enriched by the research work carried out in the four case studies.

To address the first part of RQ1, the designed systematic process consists of two phases. The first is the model configuration phase, in which relevant aspects such as the analysis of the non-BN capacity with respect to the BN as well as the BN time buffer, shipping buffer and capacity buffer of the non-BN resources.

Once the model has been defined, the second phase is the operational phase, in which the execution of the designed model is determined. For this operational execution, first, the rules and conditions that an order must fulfil to be accepted must be defined to ensure a stable system. Second, once the acceptance rules have been defined, the operational model must be implemented by monitoring and managing the buffers. Figure 35 illustrates these two phases.

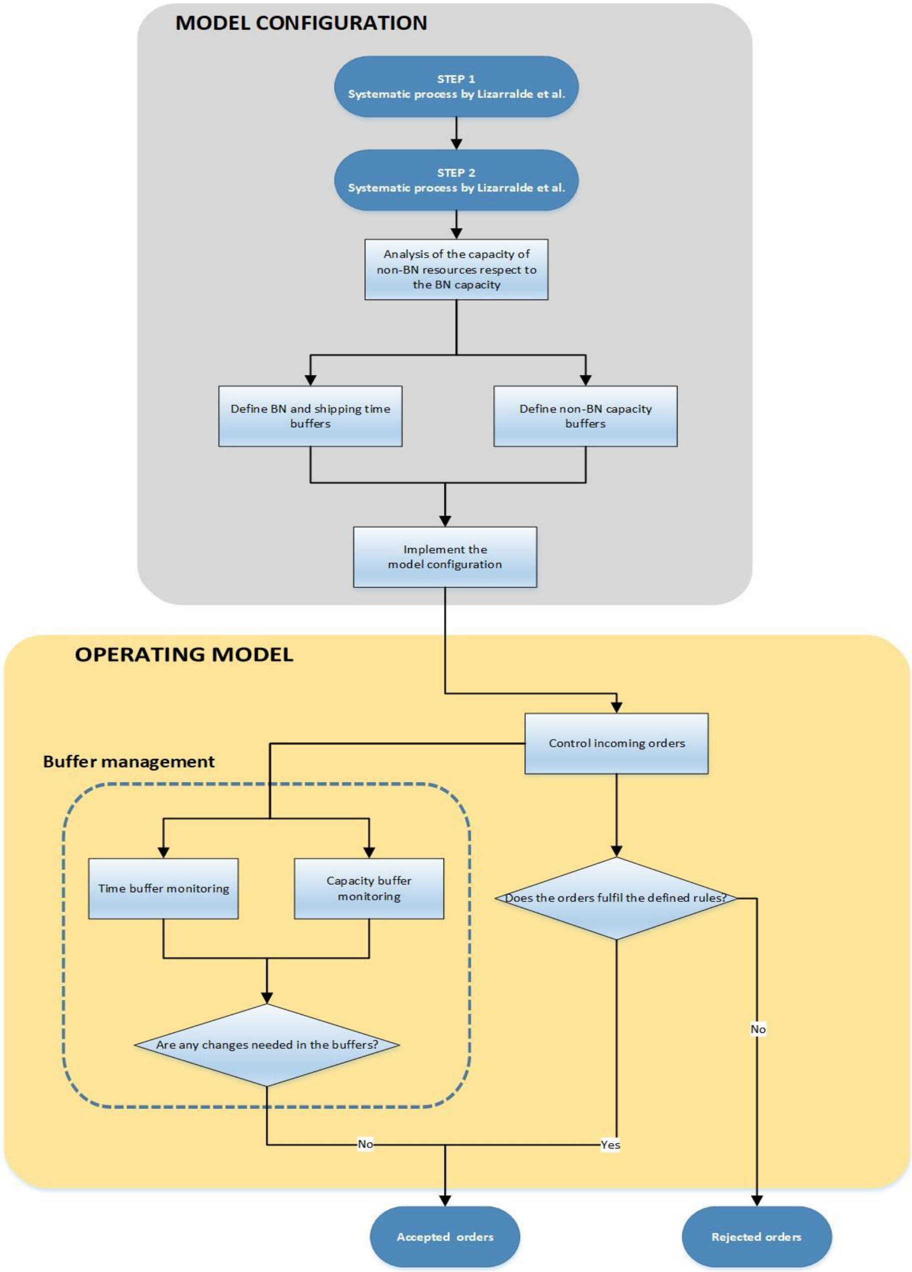

Figure 35. Model configuration phase and the operational model of the systematic implementation process

5.1.1.2 Answer to the second part of RQ1

[…] to enhance performance?

To ensure optimal system performance, it is crucial to maintain the system stability over time. To achieve this stability, the tactical and strategic horizon must be taken into account to compensate for variability in the market. Strategic sales plans can be added to the operational execution phase of the systematic process. Taking into account the projected future demand, a strategy that aligns with the supply chain capacity, internal capacity, and decision rules for accepting incoming orders must be defined.

For this reason, the tactical S&OP phase has been added to the systematic process of step three of the TOC-DBR methodology for MTO environments. In this phase, the design incorporates the S&OP process into the TOC-DBR methodology using the DDAE model. Figure 36 illustrates the complete systematic process.

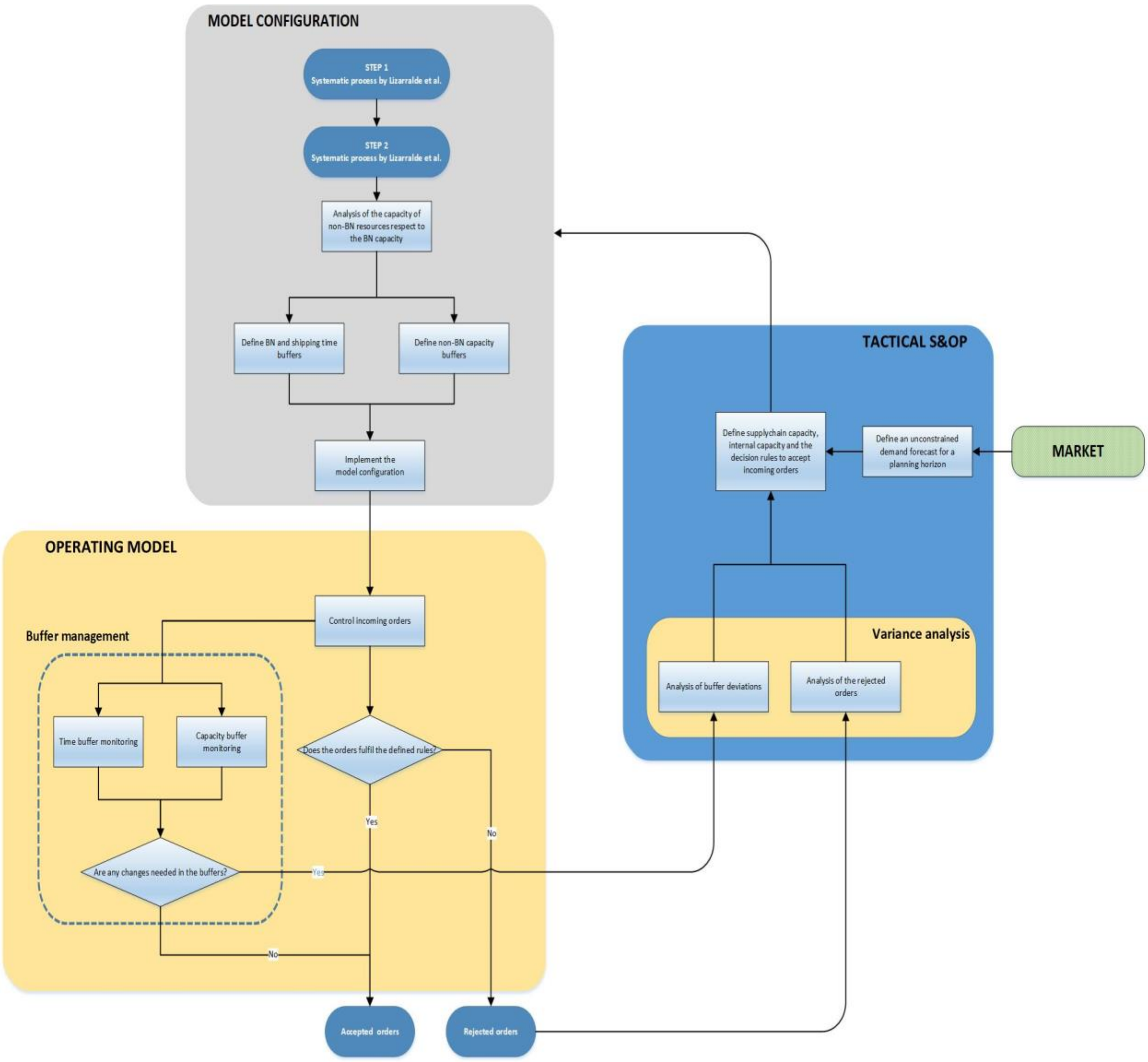

Figure 36. Systematic process for step three of the TOC methodology

The researchers hope that the designed systematic process can be applied to other MTO companies when designing the PPCS and using the DBR as a PPCS. Notably, the authors have not identified inherent limitations to the use of this process in an MTS environment, so it is believed that the systematic process can be effectively utilised in MTO and MTS environments without specific limitations or restrictions.

5.1.2 Answer to research question1a

RQ1a. How should the level of protective capacity of non-BN resources be defined?

Based on the systematic literature review, there is a clear consensus regarding the necessity of protective capacity for non-BN resources. However, determining the appropriate level of protective capacity poses a significant challenge. According to Tu et al. (2005), accurately defining the correct level of protective capacity is a complex task. Furthermore, Blackstone and Cox (2002) state that there is no mathematical approach available for precisely defining or calculating protective capacity. While it is crucial to establish an appropriate level of protection to mitigate the impact of statistical fluctuations in the system, the challenge lies in determining what qualifies as "adequate" protection (Blackstone & Cox, 2002).

From CS1 and CS3, it can be concluded that defining the necessary level of protective capacity is a strategic decision for the organisation. As mentioned in section 4.4.5, case study 3 contributions, managers of a company operating in MTO environments must understand that protection against variability must be non-negotiable if the BN schedule is to be met and a stable system is to be maintained. Seeking efficiency in a non-BN resource whose function is to protect against variability may result in insufficient protective capacity and lead to starvation in the BN. Therefore, rather than trying to mathematically guess the necessary level of protective capacity, it is preferable to hedge and adjust the level of protection until an "adequate" level of protection is reached (Orue et al., 2022).

5.1.3 Answer to research question1b

RQ1b. How can the protective capacity be managed?

In relation to RQ1a, authors such as Bessant (1998) define that key factors, such as protective capacity in this case, must be aligned with continuous improvement activities. To achieve this goal of continuous improvement, it is advisable to monitor the consumption of protective capacity and adjust the level of protection (Orue et al., 2022). For this purpose, the concept of capacity buffer from the DDAE model is integrated into the systematic process. The capacity buffer protects the control points and decoupling points from system variability. The capacity cushion can be defined as the protective capacity that provides agility and flexibility to upstream resources to adapt to system variability and that assists in managing this protective capacity (Ptak & Smith, 2018, p. 72). Furthermore, this method serves as a tool for continuous improvement of the system, as it allows adjusting the levels of protective capacity in non-BN resources through observation and analysis of their consumption. Therefore, by following this process, a manager will know how much protective capacity is necessary and how much represents an excess capacity or waste.

This management and monitoring of the capacity buffer are implemented in the operational phase – buffer management – of the systematic implementation process (Figure 37).

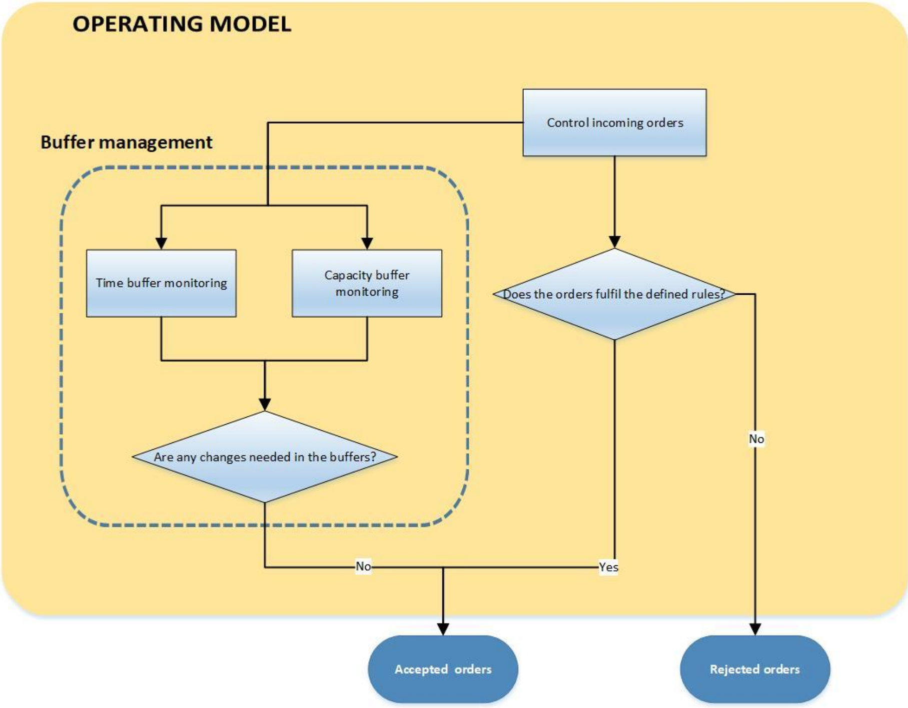

Figure 37. Buffer management in the operating model phase

Chapter 6

6 Conclusions and future research

This chapter is structured into four sections. The initial section offers an introduction to the thesis and provides a summary of the key topics covered in each chapter. The second section focuses on the contributions of the thesis, encompassing both theoretical and practical aspects. In the third section, the limitations of the current research are outlined. The fourth section presents suggestions for future research directions.

6.1 Summary of the research

This dissertation followed a defined development process and workflow. Each chapter of the thesis covers the following content:

- **Chapter 1** introduced the thesis context, highlighting the main identified problems and limitations. It also provided an overview of the thesis and described its structure.
- **Chapter 2** detailed the literature review conducted for this thesis. It covered the following main topics:
    - Characteristics of companies with MTO environments
    - TOC methodology in MTO environments
    - TOC third step systematic literature review

  This chapter also highlighted the conclusions of the general literature review and the identified gaps.

- **Chapter 3** presented the research objectives and questions. The research methodology and design concepts, the selected research strategy, the research tactics and the research programme of this thesis are explained and justified.
- **Chapter 4** describes the fieldwork of the four CSs. The process of implementing the TOC-DBR methodology and the data collected in these studies were analysed from the point of view of the application of the third step of the TOC-DBR methodology. The results and contributions of each of the cases were presented.
- **Chapter 5** presented and validated the answers to the RQs.

- **Chapter 6** concludes the thesis by presenting the final conclusions. The main contents of this chapter are the theoretical and practical contributions of the research, the research limitations, and suggestions for future research.

Figure 38 provides a visual summary of the entire research process, including the main stages, tasks, contributions, outputs and results.

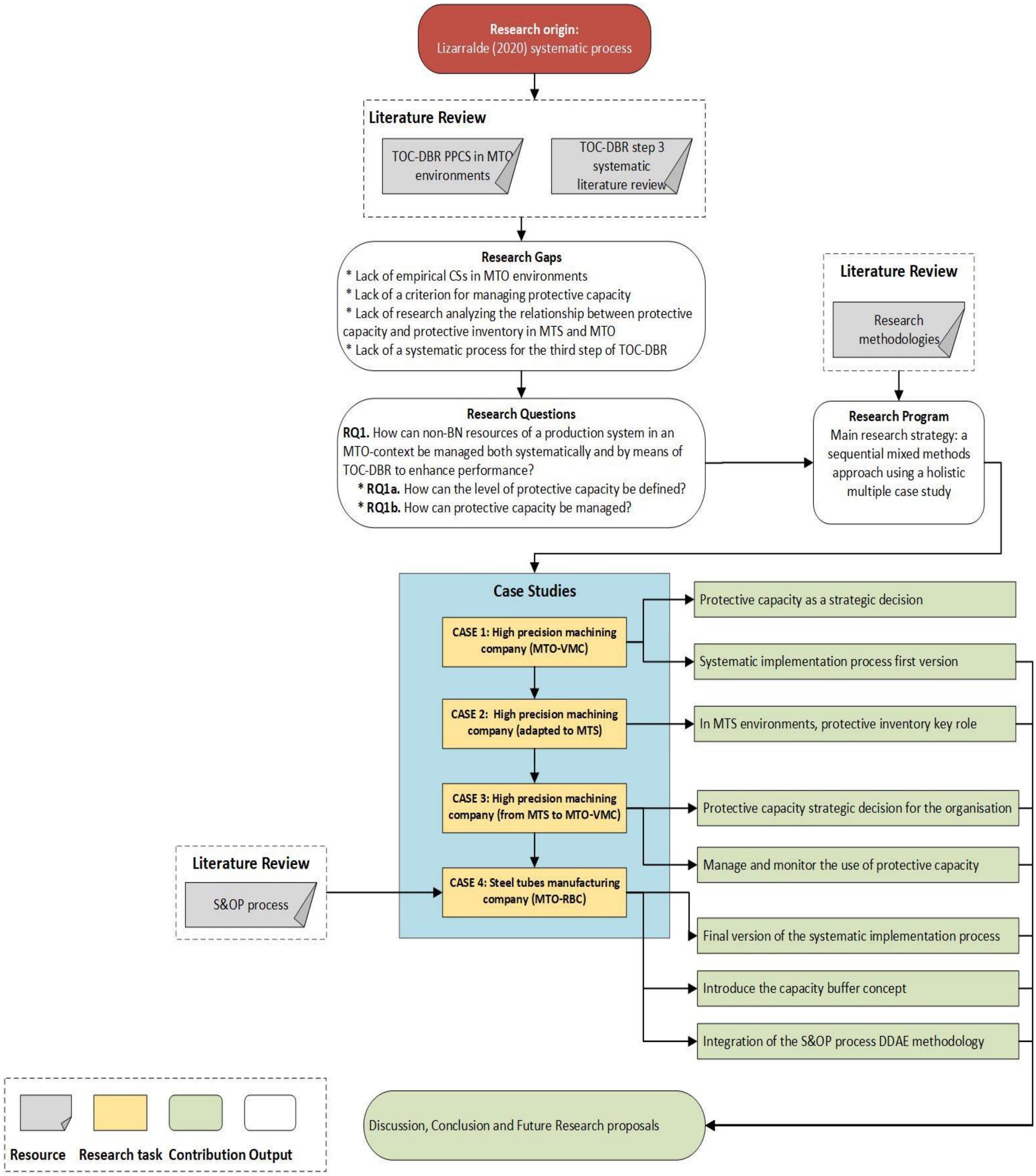

Figure 38. Flow chart of the research process

6.2 Theoretical and practical contributions

Every thesis must advance existing knowledge and make a theoretical contribution to be successful. The main research methodology of the thesis, the CS, allows for empirical research and the study of a contemporary phenomenon in its real context. Moreover, when the boundaries between the phenomenon and the context are not clearly evident, multiple sources of information are employed (Yin, 2013).

The CS is also important for capturing the emergent and immanent properties of organisational life and the flow of organisational activity, especially when it rapidly changes(Cassell & Symon, 1994).

Therefore, the following sections will discuss both the theoretical contribution and the practical contribution of this dissertation as both have been relevant in this research.

6.2.1 Theoretical contributions

The research yielded four noteworthy theoretical contributions.

C1: A systematic literature review that exclusively focuses on step three of the TOC-DBR methodology is conducted. From this systematic review, the key factors affecting the subordination of non-BNs to the system are defined.

The C1 contribution is necessary to adequately respond to RQ1. The third step of the TOC methodology addresses the subordination of non-BN resources to the system BN. Thus, it is important to understand in-depth the relevant factors that play a role in the subordination and management of non-BNs. As mentioned by Patterson et al. (2002), the BN must be protected from system variability and uncertainty to ensure that the planned throughput is not limited.

As indicated by the results of the systematic review of the literature, there are two factors to avoid the starvation in the BN. The first factor involves utilising the capacity margin in non-BN resources, which is referred to as protective capacity. The second factor involves utilising the WIP inventory positioned in front of the BN, which is known as protective inventory (Kim et al., 2010).

It can be concluded that the levels of protective capacity and protective inventory play key roles against variability (Kim et al., 2010), but as Blackstone and Cox (2002) stated, there is no mathematical approach for defining protective inventory and protective capacity.

Furthermore, in the Theory of Constraints Handbook (2010, p. 165), it is stated that

"Future simulation research on more complex plants regarding protective capacity and protective inventory is needed".

Based on C1 and the results of the systematic literature review, C2 and C3 of the dissertation explain the relationship and behaviour of the two factors affecting step three of the TOC methodology in different manufacturing environments.

C2: The impact and relationship of protective capacity and protective inventory on the implementation of step three of TOC-DBR in MTS environments are analysed.

C3: The impact of protective capacity on the implementation of step three of TOC-DBR in MTS and MTO environments is analysed.

For C2, when the protective capacity of the non-BN resources is lower than the variability of the system, the presence of the minimum level of protective inventory significantly influences the starvation of the BN. However, if the protective capacity is equal to or higher than the system variability, the presence of protective inventory does not influence the starvation of the BN. C2 suggests that in MTS environments, the presence of protective inventory plays a key role in improving overall system performance. Environments that are characterised by low variability and focused on achieving low costs (high efficiencies) and short lead times tend to have lower protective capacity. Consequently, protective inventory becomes necessary to absorb system fluctuations.

On the other hand, C3 of this dissertation shows the impact of protective capacity in different manufacturing environments. For C3, it can be concluded that the higher the variability is, the higher the level of protective capacity required for the system's BN programme to be fulfilled. Furthermore, the increase in variability and the required level of protective capacity do not increase proportionally. The increase in variability implies an exponential increase in the protective capacity required for the system to remain stable.

C4: The level of protective capacity is defined as a strategic factor or decision for organisations operating in MTO environments.

C4 of the thesis directly responds to RQ1a and states that the level of protective capacity necessary to absorb the variability of the system and to ensure that there is material in the BN is a strategic decision for the organisation. With high levels of system variability, the protective capacity must be high (with an exponential trend), which contradicts the vision of an efficient use of resources (all machines working at 100% capacity).

6.2.2 Practical contributions

The research yielded two notable practical contributions.

C5: The monitoring and management of the level of protective capacity in the TOC-DBR methodology is integrated by the capacity buffer concept utilised in the DDAE model.

C6: The systematic process of implementing the third step of the TOC-DBR methodology for MTO environments is created and described by integrating the S&OP process via the DDAE model. This integration combines two complementary methodologies: the TOC-DBR model and DDAE model.

The responses to RQs RQ1, RQ1a and RQ1b resulted in two practical contributions – C5 and C6 – regarding the implementation of the systematic process of the third step in the TOC-DBR methodology for MTO environments.

The contribution C5 of the thesis provides practical insight into how to monitor and manage levels of protective capacity using the concept of capacity buffer, which is utilised in the DDAE model (Figure 39). Additionally, this method serves as a continuous improvement tool for the system, allowing the adjustment of protective capacity levels in non-BN resources by observing and analysing their consumption. Therefore, by following this process, a manager will know how much protection is necessary and how much represents excess capacity or waste.

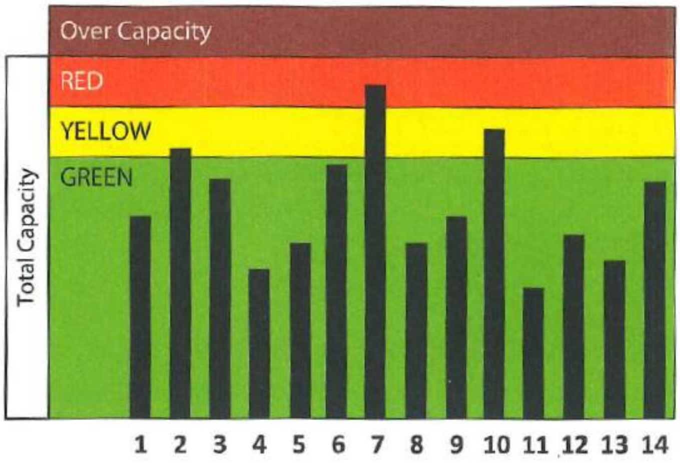

Figure 39. Capacity buffer concept utilised in the DDAE model (Ptak & Smith, 2018, p. 73)

Note that contribution C6 of the dissertation is the culmination of the entire dissertation work. By sequential investigation of CSs and specific literature reviews, an implementation process for step three of the TOC-DBR methodology for MTO environments has been designed. The implementation process suggests the steps that a manager must carry out in the implementation of step three of the TOC-DBR methodology. To ensure optimal operational performance of the system, it is crucial to maintain its stability over time. The tactical and strategic horizon must be taken into account to compensate for variability in the market, which is achieved by integrating the S&OP process through the DDAE model.

The designed process is divided into three phases, and each phase responds to a specific time range. The first phase is the model configuration phase (Figure 40), in which using the designed steps, the manager designs a solution for the implementation of the third step of the TOC–DBR methodology.

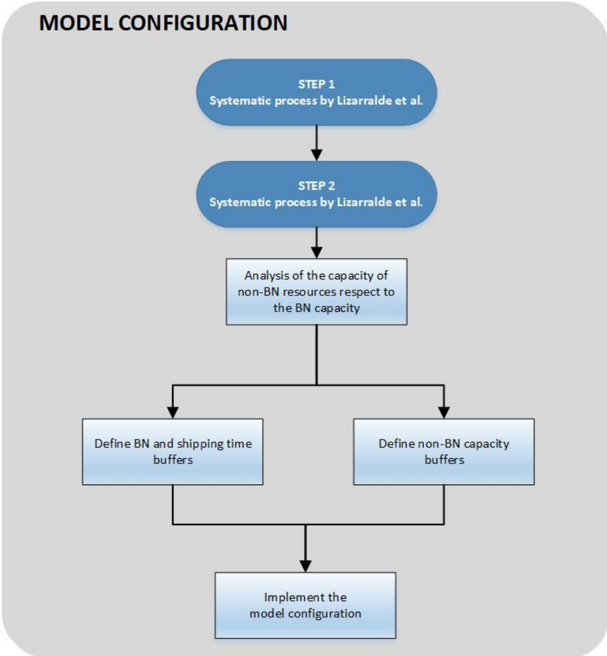

Figure 40. Model configuration phase

Once the solution design is implemented, the operational model phase follows (Figure 41). The operational model describes the steps a manager must take to control order entry and to manage both the BN and shipping time buffers as well as the capacity buffers. With these steps the manager ensures that the system remains stable in the defined time range.

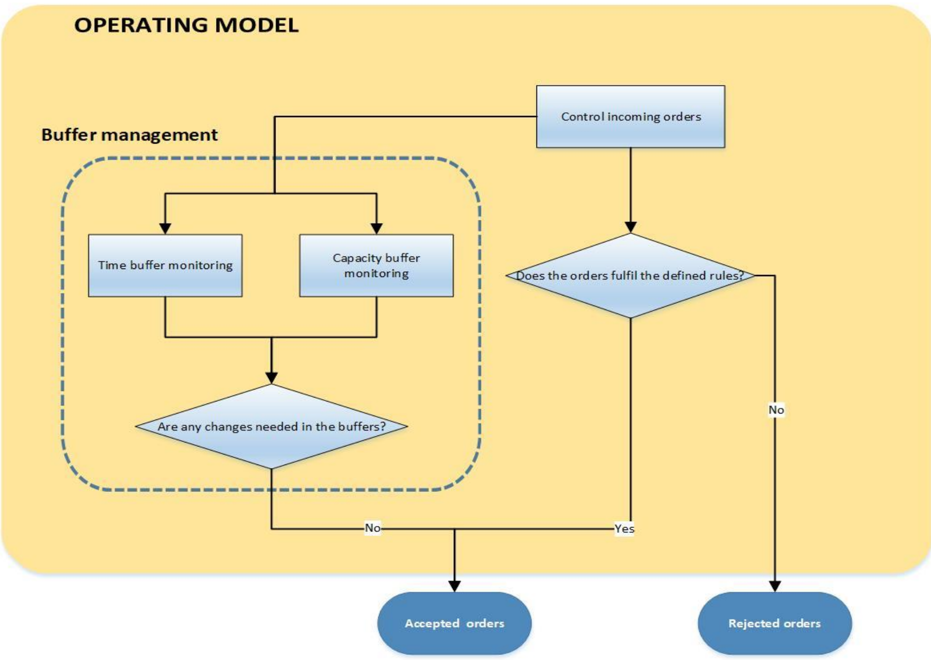

Figure 41. Operating model phase

The last phase, the tactical S&OP phase (Figure 42), defines the steps to reconcile the organisation's strategic plans with the execution phase. For this purpose, and based on the continuous improvement process of the DDAE model, the deviations of the operational phase are analysed. Taking into account these deviations, it is necessary to return to the configuration phase of the model, re-analyse the design of the solution and propose improvements to ensure that the system remains stable over time with acceptable operational performance.

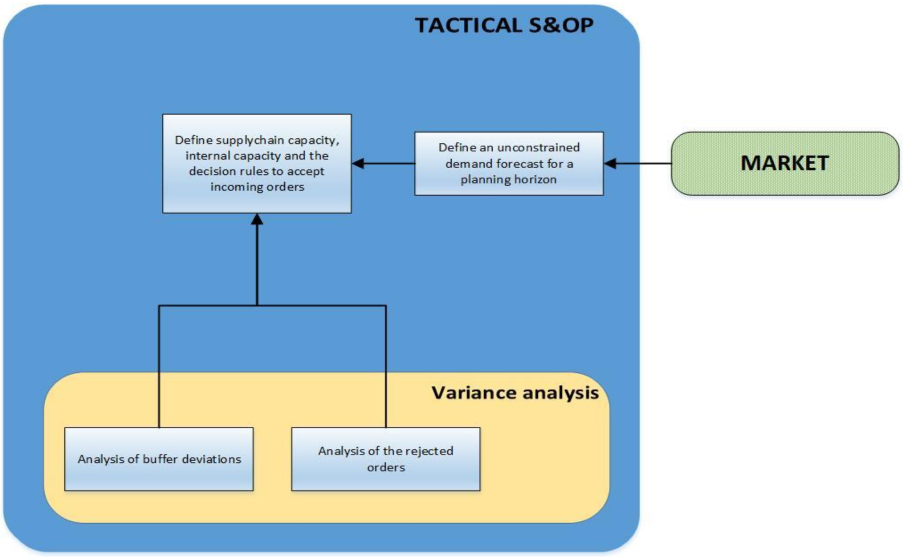

Figure 42. Tactical S&OP phase

6.3 Limitations of the research

The focus of this thesis was developing and validating a series of proposals that were generated based on the RQs. The validity of these proposals has been established through the findings and evidence gathered from both theoretical aspects and practical aspects of the research. However, it is important to acknowledge the limitations associated with the research methodology and the overall research process.

6.3.1 Limitations of the research methodology

The research methodology has many limitations that need to be taken into account. The first limitation is that the reliance on the exploration of a single case makes it difficult to generalise conclusions (Yin, 2013).

This dissertation involves four CSs. Two of the CSs are based on two industrial organisations, and the other two CSs are based on simulations designed for one of the industrial companies. Therefore, the conclusions drawn from the research cannot be considered generalisable. Further work is therefore needed in this area to strengthen and disseminate the value of the results.

The second limitation is the lack of longitudinal studies that address the evolution of the systematic process and the results obtained once it has been applied to companies.

6.3.2 Limitations of the research results

Another limitation is related to the results of the research. To increase the quality and validity of the results, it is important to define the limitations of the research results to make the process more robust.

The most important contribution of this dissertation has been the design of the implementation process of the third step of the TOC-DBR methodology for the MTO environment using four CSs. The specific context of the CSs makes the results extracted from the studies difficult to generalise to other contexts with different characteristics. In addition, the CSs are limited to a specific location and company size, which may restrict the representativeness of the sample.

The limitations mentioned above are further explained below:

- Context:
    - The two industrial case companies operated in an MTO manufacturing setting.
    - Two simulation models simulated low to high variability manufacturing environments, from MTS to MTO.
- Company Size: The two industrial companies were classified as small to medium-sized enterprises, and the largest company had an employee count of approximately 150.
- Geographical Location: The two industrial companies were located in the Basque Country, which is in the northern region of Spain. This geographical limitation resulted in a homogeneous sample in terms of location.

Although generalisation of the findings to other MTO firms may seem difficult, the researchers find no evidence that these factors are limited to the abovementioned context. There is also no evidence that the results of this research cannot be extended to engineering-to-order and MTS scenarios, to both larger and smaller companies, and to companies in other countries.

Another limitation of the research results is related to the modelling performed in the simulations. The simulations involved a series of simplifications that, although the authors believe do not limit the results, should be confirmed in real MTO-MTS environments.

The final limitation is that the research has been based on the analysis of CSs, but the designed systematic process has not been implemented in any company. Although the foundation of the designed systematic process may be robust, without the implementation of the process in a real company, its impact on operational improvements cannot be fully evaluated. The lack of real data limits the ability to demonstrate the tangible benefits of the process and its contribution to business objectives.

6.4 Future research

The research successfully achieved the initial objectives and effectively addressed the RQs. However, during the research, several potential areas for future research were identified as the results are not definitive. The following subjects are recommended for future research analysis and discussion:

- Despite the contributions made by this thesis, as mentioned in GAP 1 in section 2, Literature review, there remains a limited amount of real-world research on the application of TOC-DBR methodology in MTO environments. Consequently, there is a need for further CSs that examine the use of the TOC-DBR methodology in MTO contexts. Additionally, gaining deeper insights from various perspectives would enhance theoretical development, addressing a recognised gap in the literature and providing valuable knowledge for both academic researchers and industry practitioners.
- As mentioned in the literature, few studies analyse the relationship between the key factors – protective capacity and protective inventory – that affect step three of the TOC-DBR methodology and their sizing. Although this thesis has made many contributions regarding the relationship between them in different manufacturing environments, future research that further addresses the relationship and sizing in real manufacturing environments and thus endorses the results of this doctoral thesis is desirable.
- In the future, it would be interesting to implement the systematic process of the third step of the TOC-DBR methodology in industrial companies working in an MTO environment to validate the process. In this way, the implementation as well as the deviations and problems that have occurred can be analysed to correct any aspects that have not been taken into account.
- It would also be interesting to investigate the application of the process to engineering-to-order and MTS companies. This type of research would serve to test the systematic process, while at the same time help close the literature gap mentioned above. In addition, it could test the generalisability of the research results and provide the necessary adaptations.

- This process of implementing the third step of the TOC-DBR methodology for MTO environments is based on the systematic process of implementing the first two steps designed by Lizarralde (2020). In the future, it would be interesting to implement and validate the whole process. This approach would result in a single process that could be standardised; this standardisation would provide consistency, efficiency and continuous improvement opportunities in the process.

Chapter 7

7 References

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