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Article

Theory of constraints case study in the make to order environment

Journal of Industrial Engineering and Management (JIEM)

Provided in Cooperation with:

The School of Industrial, Aerospace and Audiovisual Engineering of Terrassa (ESEIAAT),
Universitat Politècnica de Catalunya (UPC)

Suggested Citation: Orue, Aitor; Lizarralde, Aitor; Amorrotu, Itxaso; Apaolaza, Unai (2021) :
Theory of constraints case study in the make to order environment, Journal of Industrial
Engineering and Management (JIEM), ISSN 2013-0953, OmniaScience, Barcelona, Vol. 14, Iss.
1, pp. 72-85,
<https://doi.org/10.3926/jiem.3283>

This Version is available at:

<https://hdl.handle.net/10419/261742>

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Theory of Constraints Case Study in the Make-to-Order Environment

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Received: July 2020

Accepted: November 2020

Abstract:

Purpose: The theory of constraints (TOC) drum-buffer-rope methodology is appropriate when managing a production plant in complex environments, such as make-to-order (MTO) scenarios. However, some difficulties have been detected in implementing this methodology in such changing environments. This case study analyses a MTO company to identify the key factors that influence the execution of the third step of TOC. It also aims to evaluate in more depth the research started by Lizarralde et al. (2020) and compare the results with the existing literature.

Design/methodology/approach: The case study approach is selected as a research methodology because of the need to investigate a current phenomenon in a real environment.

Findings: In the case study analysed, the protective capacity of non-bottleneck resources is found to be the key factor when subordinating the MTO system to a bottleneck (BN). Furthermore, it coincides with one of the two key factors defined by the literature, namely protective capacity and protective inventory.

Originality/value: The three key contributions of this study focus on the MTO environment as follows. The first is about identifying the key factors in subordinating the system to the BN (step 3, TOC) according to the existing literature which have been identified through a systematic literature review. The second focuses on identifying the key factors in subordinating the system to the BN through a case study. Finally, the last contribution compares the results obtained in the case study with those obtained in the literature review.

Keywords: MTO, TOC, DBR, five focusing steps; protective capacity

To cite this article:

Orue, A., Lizarralde, A., Amorrortu, I., & Apaolaza, U. (2021). Theory of Constraints Case Study in the Make-to-Order Environment. *Journal of Industrial Engineering and Management*, 14(1), 72-85.
<https://doi.org/10.3926/jiem.3283>

1. Introduction

In today's globalised environment, existing market competition has driven many companies to migrate from a make-to-stock (MTS) to a make-to-order (MTO) system, which exhibits continual growth in the number of catalogue references and reduced serial batch (De la Calle, Grus & Álvarez, 2017). In this context, MTO companies lead to non-standard product routing on the shop floor with longer lead times than MTS companies (Stevenson, Hendry & Kingsman, 2005). Accordingly, production planning and control systems (PPCSs) have become key elements in managing material flow in production plants (Jaegler, Jaegler, Burlat, Lamouri & Trentesaux, 2018).

Several studies have focused on the drum-buffer-rope (DBR) methodology in MTO environments. Theory of constraints (TOC)-DBR has proved to be a valid methodology for responding to the problems of MTO environments (Chakravorty, 2001; Darlington, Francis, Found & Thomas, 2015; Modi, Lowalekar & Bhatta, 2019; Riezebos, Korte & Land, 2003). However, other studies have detected difficulties in implementing TOC-DBR (Atwater & Chakravorty, 2002; Pretorius, 2014; Wu & Yeh, 2006). To overcome these issues, Lizarralde, Apaolaza and Mediavilla (2020) developed a systematic decision-making process to apply DBR in MTO scenarios by proposing a change in the first two steps of TOC methodology. The present research analyses the DBR implementation carried out by Lizarralde et al. (2020); the objective is to identify the key factors of the implementation on the third TOC step and compare the results with the existing literature to advance the proposed systematic decision-making process.

This article begins with a literature review in Section 2, where the existing literature on TOC-DBR methodology in MTO companies is analysed with a focus on implementation problems. In Section 3, a systematic review of the literature in the mentioned field is carried out, taking into account that the research will focus on the identification of the key factors when implementing the third step of TOC-DBR. In Section 4, the objectives of the article and the research question (RQ) are defined. Afterwards, in Section 5, the selected research methodology is presented through a case study. The discussion continues in Section 6 with the analysis of the case study, the participation of the researchers and the results obtained. In Section 7, the degree to which the research objectives are achieved is analysed. Finally, the conclusions and future lines of research are presented in Section 8.

2. Literature Review

TOC is a management methodology based on systems thinking (Boyd & Gupta, 2004). Its main idea is that every system has at least one constraint that limits its performance. This constraint is taken as the basis for managing and improving the system (Goldratt & Cox, 2004). According to Goldratt and Cox (2004), a constraint or bottleneck (BN) is anything that limits a system from achieving higher performance versus its goal.

The five steps of TOC are as follows: (1) identify the system's BNs, (2) decide how to exploit the BNs, (3) subordinate everything else to the above decision, (4) elevate the system's BNs and (5) if a BN has been broken in a previous step, return to Step 1.

The TOC scheduling mechanism, DBR, is a PPCS in shops with BNs, and it addresses both market and physical constraints (Thürer, Stevenson, Silva & Qu, 2017). To control the whole system, only accuracy in the BN is required, so DBR is a simple approach to carry out (Gupta & Snyder, 2009). Once the restriction is identified, DBR synchronises the production with the customer's needs through the rope. It connects the work input with the BN (Thürer et al., 2017). The BN programme is scheduled according to the company's sales portfolio, and the programme criteria are previously defined in the system-exploiting step. Finally, DBR uses drum and shipping buffers (time or amount of time equivalent to work in progress (WIP)) to allow synchronisation and, at the same time, protect the system's performance from variability with low levels of WIP (Thürer et al., 2017). Generally, non-BN resources are not programmed because each operation is governed by the consumption of the buffer (Goldratt & Cox, 2004).

Several studies validated the TOC-DBR methodology for a MTO environment by demonstrating its beneficial effect on workflow performance through reduced lead times and cycle times and increased revenue (Chakravorty, 2001; Darlington et al., 2015; Modi et al., 2019; Riezebos et al., 2003). However, other studies showed the difficulties in implementing the TOC-DBR methodology in this changing environment. Atwater and Chakravorty (2002) defined several issues, such as quantifying the additional capacity of non-BN resources and the appropriate identification of the BN, by considering that real environments represent temporary situations and are not realistic. By contrast, Wu and Yeh (2006) analysed the complexity of implementing the DBR methodology in complex manufacturing environments, focusing on BN re-entry flows and the importance of BN resource sequencing. Finally, Pretorius (2014) identified the shortcomings for decision making that facilitates moving from one step to the next, in addition to the lack of clarity around the ideal location of constraints.

Several researchers have worked on a series of alternatives to solve the problems raised in the previous section. Pretorius (2014) proposed a decision map that included the five steps of the TOC methodology; the map defined a

series of strategic points that help the company make the right decision and allow them to move from one step to the next. By contrast, Lizarralde et al. (2020) provided a strategic perspective for selecting and exploiting BNs. The researchers developed a systematic decision-making process that systematised the first two DBR stages. As shown in Figure 1. Systematic process for steps 1 and 2 of theory of constraints methodology (Lizarralde et al., 2020), the researchers provided a set of four criteria to define how the BN is selected. In addition, three operative sub-steps for deciding how to exploit the BN are included.

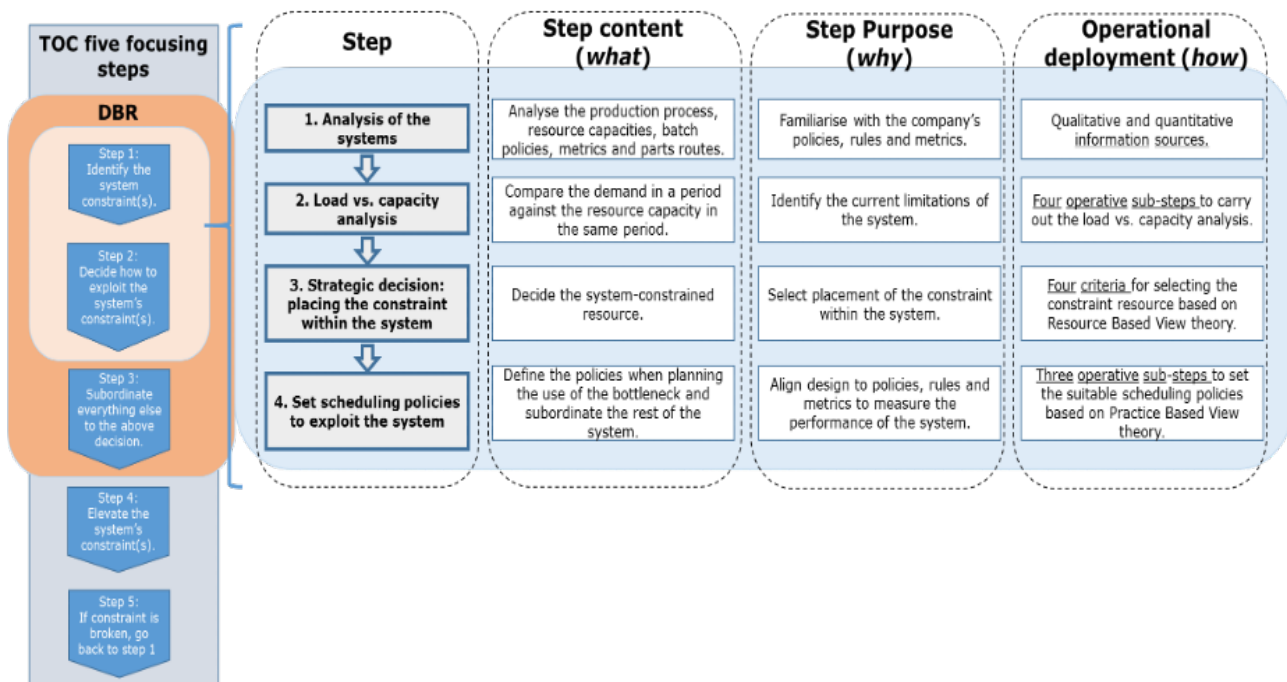


Figure 1. Systematic process for steps 1 and 2 of theory of constraints methodology (Lizarralde et al., 2020)

3. Systematic Literature Review of TOC Third Step

TOC step 3 deals with the resources that are non-constraints, which require them to work in a way that supports the constraint. Non-BN resources have more capacity than constraints do by definition, and thus doing more than the needed work will only produce WIP that the BN is not able to take on. Step 3 only deals with the management of non-BN resources and their level of utilisation, which is determined by the capacity and utilisation of the constraint rather than the potential of the non-constraint resources (Goldratt & Cox, 2004).

To deepen the third step of TOC, a systematic review of the literature is carried out. A systematic literature review is conducted to assess and identify research that is relevant to a particular RQ, topic area or phenomenon of interest (Kitchenham, 2004). It is necessary to define a research strategy to carry out an adequate and comprehensive systematic review (Kitchenham, 2004). This literature review uses a strategy based on Kitchenham (2004) and is detailed in Figure 2. Systematic literature review methodology based on Kitchenham (2004).

3.1. Planning the Review

This study is motivated by the possibility of deepening the systematic implementation of the TOC-DBR methodology following Lizarralde's (2020) systematisation of the first two steps. The aim of this literature review is to analyse existing research on the implementation process of the third step of TOC-DBR in MTO environments and, more specifically, the identification of the key factors when subordinating the system to a BN.

When planning the literature review, it is necessary to define a protocol that details the methodology used for conducting a specific systematic review. A defined protocol is needed to reduce the effect of researchers' bias (Kitchenham, 2004).

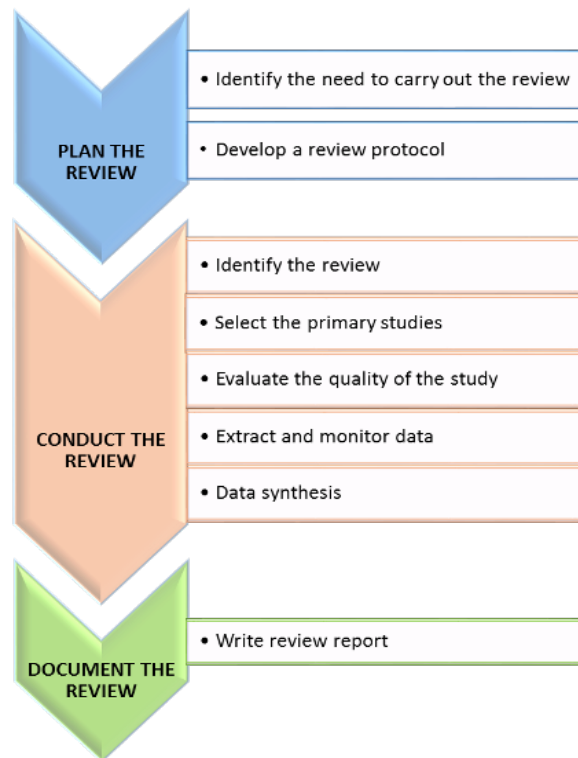


Figure 2. Systematic literature review methodology based on Kitchenham (2004)

The defined protocol is as follows:

Keywords to Carry out the Literature Review

The articles focus exclusively on the third step of TOC, which can be defined as the subordination of everything to the BN. Therefore, all the concepts related to this step were entered into the search engine for title, abstract and keywords. All the combinations used are presented below:

- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘capacity margin’
- ‘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’ AND ‘variability’
- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘step 3’
- ‘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 ‘problem’
- ‘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 ‘scheduling problem’
- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘protective inventory’ OR ‘protective capacity’
- ‘Bottleneck’ AND ‘protective capacity’
- ‘Drum buffer rope’ OR ‘DBR’ OR ‘theory of constraints’ OR ‘TOC’ AND ‘capacity management’

The Sources to Identify Primary Studies

Scopus and Web of Science were the databases chosen for the research. They are two of the largest available databases of citations and abstracts of peer-reviewed literature and include all major operations and management publishers that are indexed. Additional potential articles were also identified by searching Google Scholar.

Select the Exclusion and Inclusion Criteria for the Studies

The criteria used to select, analyse and evaluate the articles were as follows: (1) exclusive focus on the third step of TOC; (2) publication in an academic journal or conference; (3) included case studies, both simulated and real; (4) inclusion of no other methodology; and (5) exclusion of articles written for a final bachelor or master's degree.

Period of Publication

The delimited publication period was from 1990 to 2020. The year 1990 was chosen as the beginning of the publication period because it denotes when the TOC-DBR methodology began to attract the attention of several key authors. The year 2020 was defined as the end date of publications to maximise the number of studies with as many updates as possible.

Study Quality Assessment

Both quantitative and qualitative documents were considered for this research. The indicators used to evaluate the quality of the selected journals were the Journal Citation Report and SCImago Journal Rank.

3.2. Conduct the Review

An unbiased search strategy was defined to find as many primary studies related to the third step of the TOC methodology as possible.

Given that few studies make a direct reference to the implementation process of the third step of TOC, the first decision was to select the terms ‘theory of constraints’ or ‘TOC’ and ‘drum buffer rope’ or ‘DBR’. This choice of keywords was intended to ensure that TOC-DBR would be the main theme of the article. To refine the search and focus on the implementation of the third step of TOC, key terminology that relates with the subordination of the system to the BN was added. Figure 3. Literature review selection process illustrates the selection process carried out.

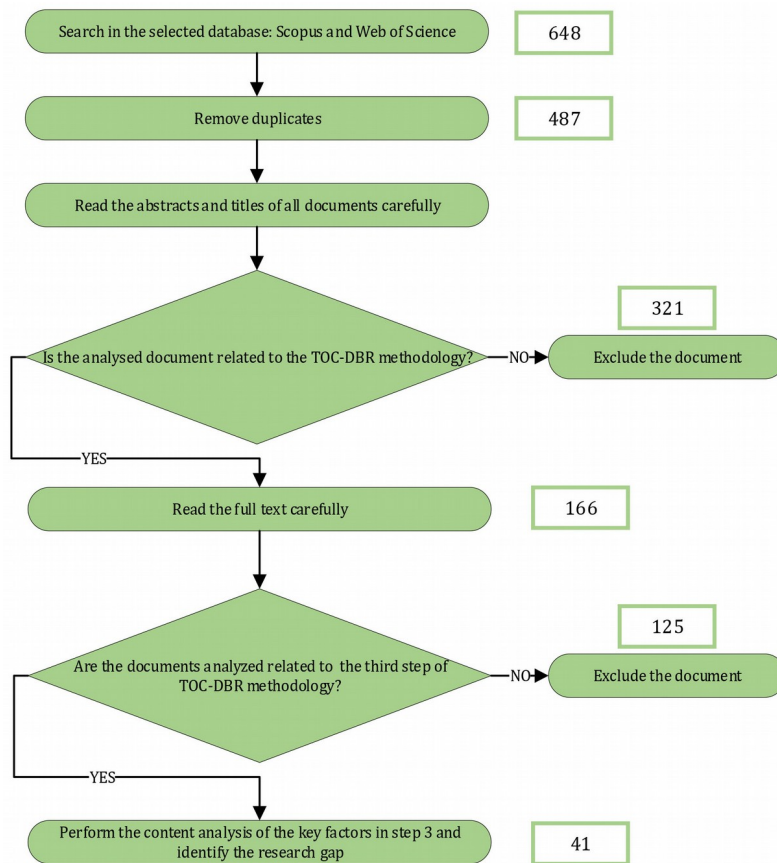


Figure 3. Literature review selection process

Following this process, 41 articles remained, and these were carefully reread again. Figure 4. Frequency of TOC-DBR selected papers, 1990-2020 and Figure 5. TOC-DBR selected articles in journals by publisher show the 41 analysed articles by publication year and journal of publication, respectively.

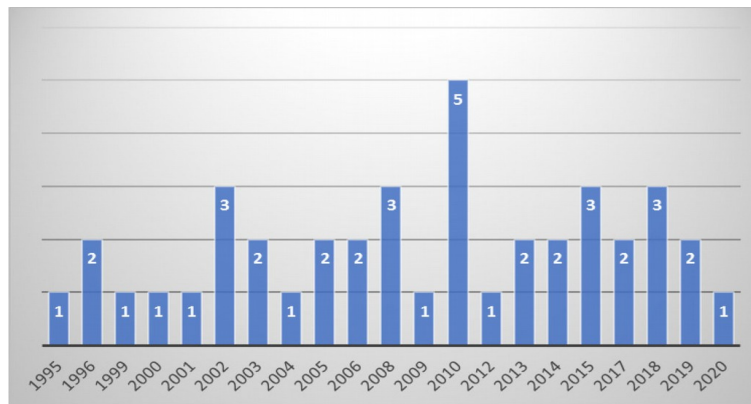


Figure 4. Frequency of TOC-DBR selected papers, 1990-2020

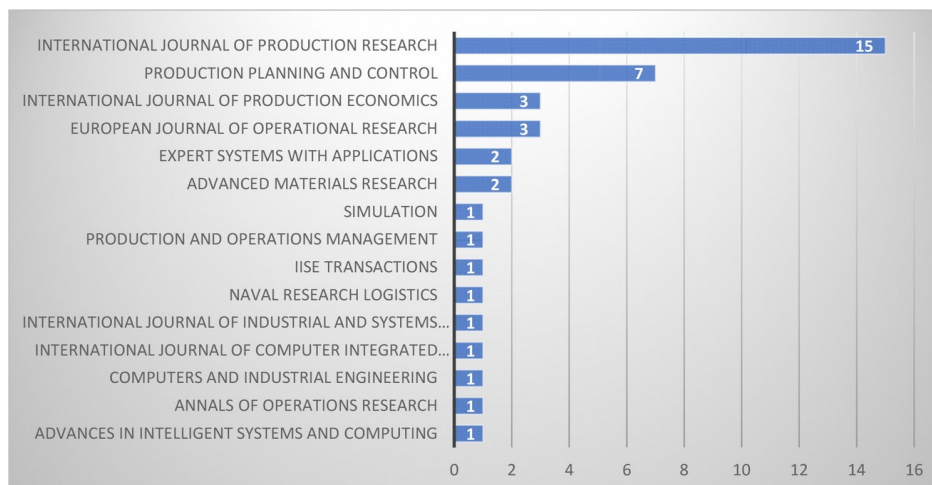


Figure 5. TOC-DBR selected articles in journals by publisher

3.3. Document Review

As mentioned in the Section 3, Step 3 deals with the resources that are non-constraints, which require them to work in a way that supports the constraint. This critical constraint should be protected from variation and uncertainty within the system to ensure that the planned throughput is not limited (Patterson, Fredendall & Craighead, 2002).

This variability in the system can generate that non-constraint work stations would starve the constraint work station. In other words, the constraint work station can be available to work, but the resource has no work to perform. This condition, called constraint starvation, occurs when the WIP has not reached the constraint work station (Blackstone & Cox, 2002). There are two different methods to reduce starvation in the BN. The first one uses the capacity margin in non-BN resources (protective capacity), and the second one uses the WIP inventory in front of the BN (protective inventory) (Kim, Cox & Mabin, 2010).

3.3.1. Protective Capacity

To understand what protective capacity means, it is important to know some basic terms. As revealed in Figure 6. Productive and idle (protective and excess) capacities (Kim et al., 2010), capacity can be classified into two major types, productive and idle.

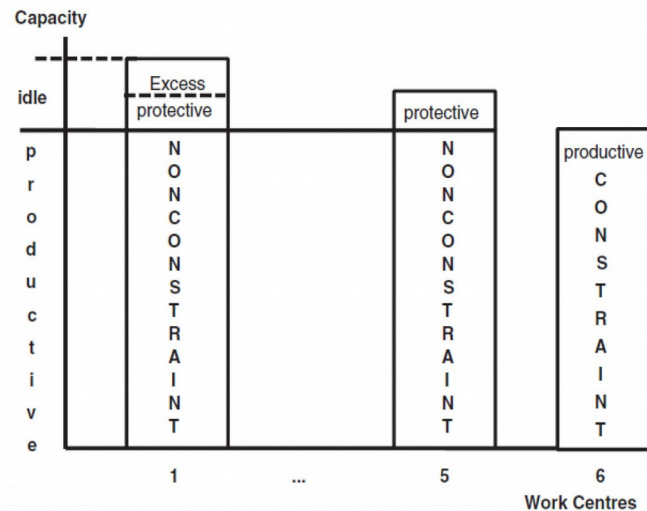


Figure 6. Productive and idle (protective and excess) capacities (Kim et al., 2010)

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

Idle capacity is defined as ‘the available capacity that exists on non-constraint required to support the constraint. Idle capacity has two components, protective capacity and excess capacity’ (Pittman & Atwater, 2016: page 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: page 149). Meanwhile, Blackstone and Cox (2002: page 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 utilization of the constraint work station’.

From the literature review, it can be concluded that protective capacity plays a key role in the system’s performance. Atwater and Chakravorty (1994) explained that the use of protective capacity is a key factor to achieve faster cycle times while operating at lower inventory levels. Caridi, Cigolini and Farina (2006) defined that protective capacity plays a relevant role in determining productivity. Atwater and Chakravorty (2002) showed that protective capacity at the second most heavily utilised station can improve the system’s performance. Craighead, Patterson and Fredendall (2001) confirmed earlier studies showing that the placement of protective capacity could reduce mean flow time. Lawrence and Buss (1994) reported that higher levels of protective capacity decreased BN shiftiness at all BN utilisation levels.

From the studies analysed, there is no doubt about the need for protective capacity in non-BN resources. However, as defined by Tu, Chao, Chang and You (2005), it is very difficult to determine the correct protective capacity. Patti, Watson and Blackstone’s (2008) research article focused on the amount of protective capacity necessary to achieve improvements in production and distribution or the shape of that protective capacity in production systems. Craighead et al. (2001) conducted a systematic investigation of how protective capacity impacts system performance. In the future lines defined by Caridi et al. (2006), protective capacity is described as a viable means for realising faster cycle times and reducing inventory. However, this extra capacity also has a cost connected to it. Hence, there are additional research paths that can be worked on.

3.3.2. Protective Inventory

To understand what protective inventory means, we will follow the same logic as that for protective capacity. Inventory has similar implications and definitions as capacity (Blackstone & Cox, 2002).

Productive inventory is defined as the amount of WIP inventory (measured in time units) needed to support the constraint until the material can get from the first 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: page 83).

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

Protective inventory has similar concerns as protective capacity. Several studies talk about the need for protective inventory to protect the throughput from variability. Blackstone and Cox (2002) spoke about the amount of protective WIP that is used to reduce the impact of statistical fluctuation at the non-constraint work stations on the constraint work station and system throughput. Betterton and Cox (2009: page 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. It is WIP inventory that the constraint needs for uninterrupted operation in a non-deterministic system’.

There are certain formulas that aim to calculate the productive inventory needed in the system to maximise the throughput. For example, Schragenheim and Ronen (1990) described a process for setting these buffers, which starts by simply dividing the current lead-time allowance of the company in half and using one portion as the constraint buffer and one portion as the shipping buffer. Managers can use this approach to determine initial buffer sizes and make adjustments over time until optimal buffer sizes are identified.

However, as indicated by Blackstone and Cox (2002), there is no mathematical approach for defining protective inventory (or protective capacity). Although an adequate level of protection is needed to reduce the impact of statistical fluctuations in the system, the difficulty comes in defining the ‘adequate’ protective inventory (Blackstone & Cox, 2002). As the risk of excess inventory is the increase in WIP and the addition to the production lead time, the minimum levels of protective inventory should therefore be identified (Khalil, Stockton & Fresco, 2008).

From the comprehensive literature review analysis, it can clearly be concluded that the levels of protective capacity and protective inventory play key roles against variability. These protection levels will determine the cycle time and throughput of the system.

Nevertheless, as Blackstone and Cox (2002) stated in their conclusions, there is no mathematical approach for defining protective inventory and protective capacity. In addition, it is not clear where protective capacity should be placed.

Finally, note that a dilemma exists between protective capacity and protective inventory (Figure 7. Dilemma between protective capacity and protective inventory). High levels of protective inventory increase WIP and cycle time, whereas an excess of protective capacity leads to the improper management of the resource. Both situations are not aligned with the TOC philosophy.

In consideration of these research areas, the objective of the study is defined in the next section.

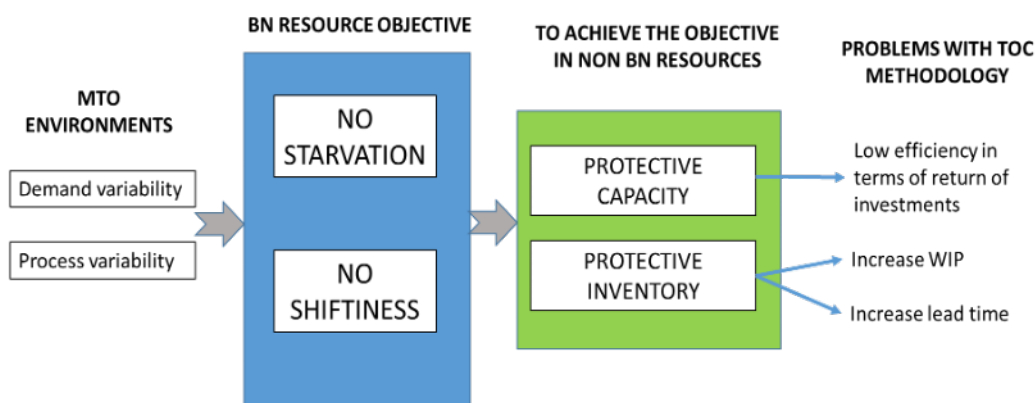


Figure 7. Dilemma between protective capacity and protective inventory

4. Objective

The aim of this study is to identify the key factors in subordinating the system to the BN (step 3, TOC) in MTO environments. Specifically, it expands on the work carried out by Lizarralde et al. (2020) and compares the resulting key factors with the existing literature. To this end, a case is analysed to try to address the following research question (RQ):

RQ: What are the key factors that influence the subordination of the third step of TOC to enhance operative performance in the DBR implementation in MTO environments?

Operative performance can be measured in different ways. In this case, the three priority indicators of the case study company are used:

1. On time delivery
2. Manufacturing lead time
3. Inventory level

5. Research Methodology

The case study approach was selected as a research methodology because of the need to investigate a current phenomenon in a real environment. A case study provides rich knowledge about the specific context to be investigated (Yin, 2018). The research methodology used in this case study is based on an exploratory and descriptive approach, following a qualitative research strategy (Robson, 2002). The unit of analysis to be investigated was a single case study of a company, where the implementation of TOC was analysed, with a focus on the third step of the methodology. Information was collected through semi-structured interviews with the main agents carrying out the implementation (Yin, 2018).

6. Case Analysis

6.1. Previous Work: DBR Implementation Process

The case study company where Lizarralde et al. (2020) implemented the DBR process is a leader in the high-precision machining market. Located in the Basque Country (Spain), it specialises in providing customised solutions to its customers who are spread throughout the world (e.g. vacuum chambers, complex structures, pressure vessels). Its manufacturing assets include different technologies, such as cutting, shot blasting, pickling and passivating, press forming, welding, painting and machining. Lizarralde et al. (2020) considered this case to be a valuable study because it represented a real MTO company. Two types of manufacturing scenarios exist amongst MTO environments: repeat business customizers and versatile manufacturing companies (VMCs) (Amaro, Hendry & Kingsman, 1999). The case study company can be defined as a VMC. It is organised in a functional way (job shop) and has a high complexity of management due to the casuistry of its material flows.

Lizarralde et al. (2020) found that the planning process was focused on maximising the performance and production of all sections with a local vision. Therefore, each section developed a weekly production plan based on production orders with the objective of 'hours worked per day'. This approach resulted in the company having problems in meeting the expectations of timely delivery to the customer, even though the management team thought the existing capacity was large enough to complete the work according to the due dates. To solve this problem, the TOC-DBR methodology evolution developed by Lizarralde within his line of research was applied (Lizarralde, 2020; Lizarralde, Apaolaza & Mediavilla, 2019; Lizarralde et al., 2020). This methodology evolution included a systematic implementation process for the first two steps. First, a system analysis was performed, where the manufacturing process, resource capacities, batch policies, metrics and part routes were analysed. Next, a load versus capacity analysis was conducted. The objective was to compare the demand over a certain period against the capacity of the resources in the same period. In the next step, a strategic decision was made on where to place the restriction within the system. In this case, it was decided that precision machining was the BN. Finally, scheduling policies were defined to exploit the system, specifically, policies about when to plan the use of the BN and the subordination of the rest of the system.

Note that whether the operations before and after the BN would have enough capacity was a critical factor considered when subordinating the system to the BN. Figure 8. General material flow in the case study company (Lizarralde et al., 2020) shows the resulting DBR solution design.

The most relevant results obtained after the DBR implementation, including the systematic process of the first two TOC steps, were 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%.

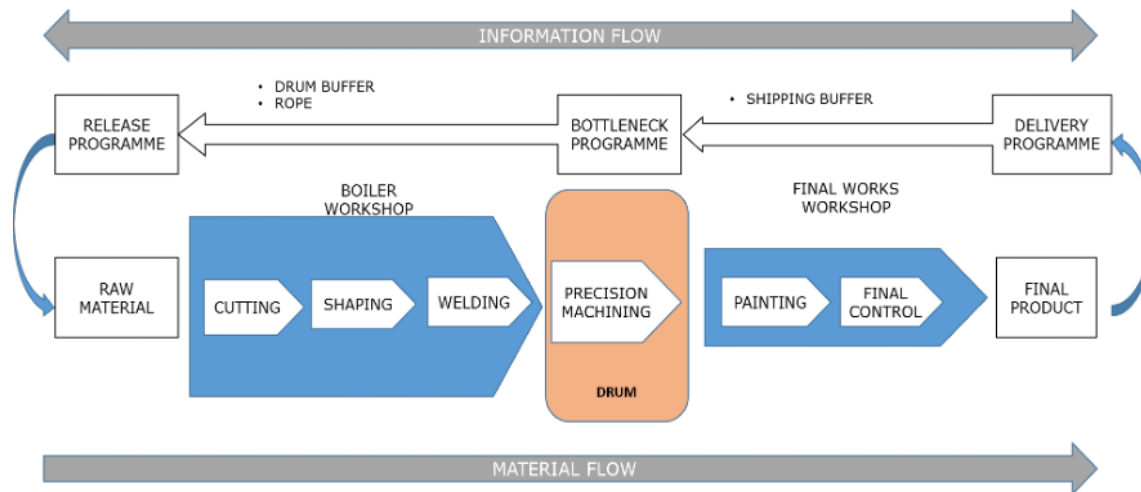


Figure 8. General material flow in the case study company (Lizarralde et al., 2020)

6.2. TOC Step 3 Analysis

The analysis and data collection were carried out through semi-structured interviews, where four managers from the company and Lizarralde (the person who led the implementation process) participated. During the interviews, they were asked about the implementation approach, with a focus on the third TOC step. All the answers revealed that the respondents had some problems in implementing the designed model. At times, the BN programme did not receive material from previous operations even though it supposedly had enough capacity. This problem stemmed from the great diversity of products. Such diversity introduced variability into the production system, which made it difficult to determine the true workload and capacity because the process times were difficult to estimate precisely. For example, the order book was small, and new orders were extremely different from one another, ranging from a pump for a hydroelectric power station to a vacuum chamber for a scientific project.

As mentioned above, resource load was challenging to predict because of system variability, which meant that it was sometimes impossible to carry out the planned work.

To find the root cause of the problem, the work programme was launched and which non-BN resource was not capable of producing the planned work was analysed. It was observed that material to be processed accumulated in the welding area, thus causing starvation in the BN. This problem did not occur for the rest of the non-BN resources.

In consideration of the root cause and with the aim of solving the lack of material in the BN, the capacity of the welding area was increased by 27% from 30 to 38 welders. The quantification of this increase was taken on a trial basis from the time the programme launched. That is, the capacity of the welding area was increased until there was no starvation in the BN.

This 27% increase in capacity gave stability to the BN programme and ensured that the BN does not change its location and remains in the place that was strategically chosen.

The main results achieved in the implementation were an increase in service level (20%) and reductions in manufacturing lead time (10%) and current stock (20%).

7. Discussion

This section aims to demonstrate that the research objectives were achieved by providing an unambiguous and adequate answer to the RQ. To this end, an overall analysis of the results obtained from the case study presented in the previous section was carried out.

RQ: What are the key factors that influence the subordination of the third step of TOC to enhance operative performance in the DBR implementation in MTO environments?

A key factor was identified as follows.

Protective capacity: ensuring a ‘sufficient and necessary’ capacity of non-BN resources.

MTO companies are difficult to manage due to the existing variability. This variability turns out to be higher in VMC-type companies because the demand and workflow casuistry are very complex, which makes it difficult to define the workload of each resource (Stevenson et al., 2005). For this reason, the system must be protected against this variability (Patterson et al., 2002).

This protection of the system is difficult to quantify given that variability in this environment changes according to the existing demand (Tu et al., 2005). Consequently, the use of protective capacity turns out to be a strategic decision of the company. Thus, to ensure satisfactory overall performance, the company must have protection against uncertainty at all times. It will likely lead to non-BN resources being idle at times.

As mentioned above, the quantification of protection is a difficult aspect to define. Consequently, the definition of an implementation process will help carry it out satisfactorily. This implementation process can be divided into two phases.

In the first phase of design and validation, both the buffers 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.

The second phase corresponds to 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. To do this, the system must control the incoming orders in addition to managing the buffers.

Figure 9. Implementation process of step 3 shows the designed implementation process.

By identifying the key factor and demonstrating the improvement in operative performance, we can state that the research objectives were achieved and the RQ was answered.

8. Conclusion and Future Research

Companies working in MTO environments have several difficulties in managing production plants because of market uncertainty, that is, they cannot predict demand accurately. For this reason, the appropriate choice of the PPCS is relevant. As presented in this article, several authors have demonstrated that implementing TOC-DBR in MTO environments could provide superior performance and an easy-to-use approach. However, other studies have shown the problems in implementing the mentioned methodology in this changing environment. To solve these implementation problems, authors like Lizarralde et al. (2020) have created a systematic process for the first two TOC steps. In this article, the TOC-DBR methodology was studied by implementing the mentioned systemic process. In conclusion, the implementation of the systematic process of the first two steps is not enough to obtain satisfactory results. Even if the first two steps of the systematic process are carried out correctly, if the third step is not correctly analysed and defined, then the result obtained may not be the one expected.

The main contribution of this article is the identification of implications when implementing the third step of TOC. From the conclusions of the literature review in step 3, the two key factors when implementing the third step of TOC-DBR are defined, protective capacity and protective inventory.

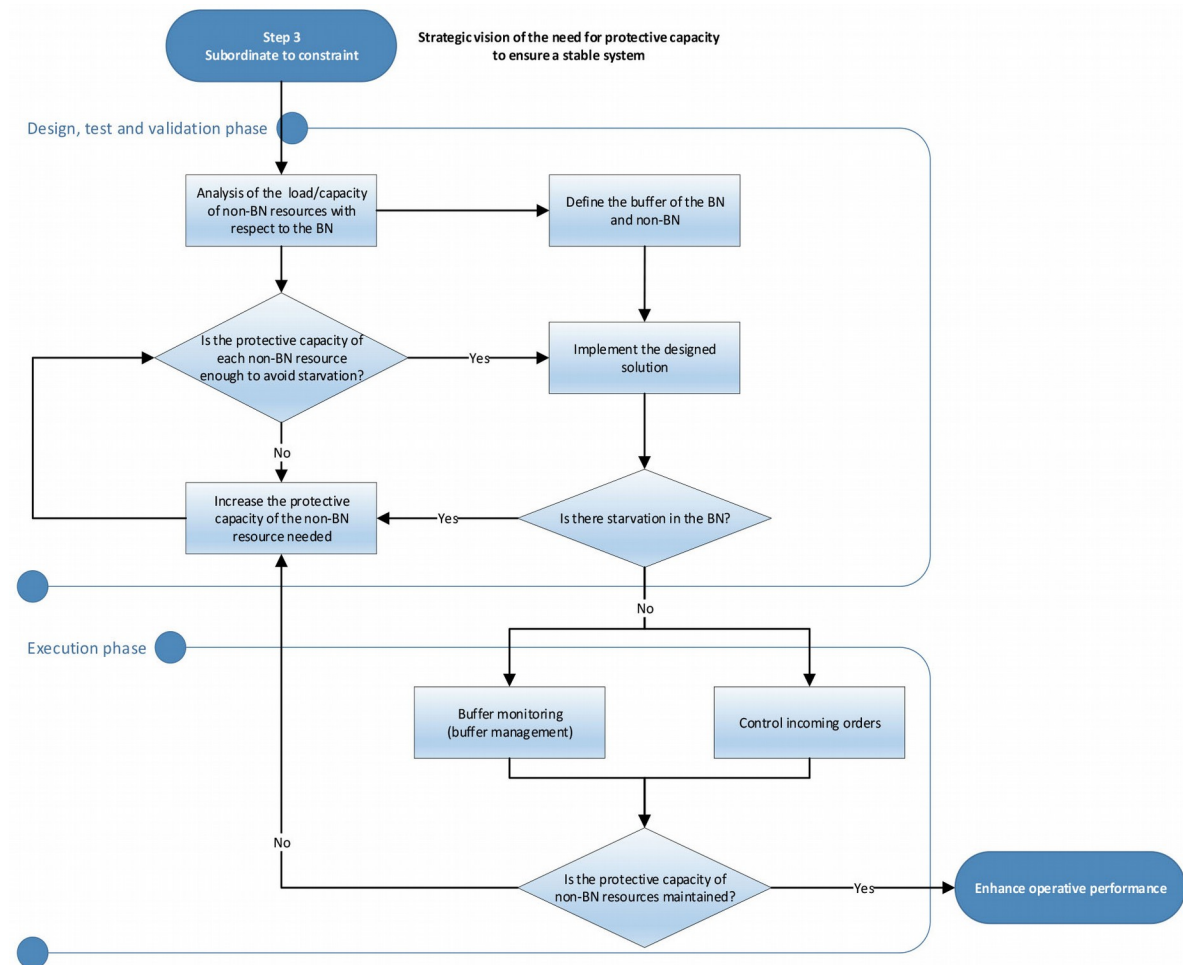


Figure 9. Implementation process of step 3

However, in this article's case, the key factor in subordinating the system to the BN was shown to be protective capacity. Initially, the subordination of the system to the BN was not carried out properly 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. The protective capacity of non-BN resources had to be higher in MTO than in MTS scenarios to ensure that the system BN would continue to be chosen. Thus, the definition of protective capacity ends up being a strategic decision because the more complex the MTO environment, the greater the needed protective capacity.

As a conclusion, the key factor defined in the case study, namely protective capacity, coincides with one of the two key factors defined by the literature.

A failure in any step of the execution of TOC causes the system to work improperly. Therefore, a line of future investigation could be to continue examining the implementation process created by Lizarralde et al. (2020) and proceed to the execution of the third step, which is the subordination of the system to the BN. The key factors should also be validated. To deepen the implementation of TOC-DBR in MTO environments, we invite other authors to continue researching and defining the implementation process.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The authors received no financial support for the research, authorship and/or publication of this article.

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