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Organization and management of enterprises

RESEARCH ARTICLE

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ABSTRACT:

This study uses simulation to analyse the impact of protective capacity in the implementation of Step 3 of the theory of constraints (TOC) methodology in make-to-order (MTO) environments. The results suggest that at different levels of variability, different levels of protective capacity are needed to keep a system stable and meet the bottleneck (BN) schedule. The higher the variability, the higher the level of protection needed. The definition of the level of protective capacity required is a strategic decision for the organisation, as it must be emphasised that with high levels of variability in a system, the protective capacity must be very high, which contradicts the efficient use of resources. However, for managers to know and control how much protection is needed without the need for additional capacity, it is advisable to monitor the use of protective capacity. This concept of protection monitoring and control is relatively new in the TOC–drum-buffer-rope (TOC-DBR) methodology, but it is applied in the demand-driven adaptive business model and, therefore, should be integrated into the TOC-DBR methodology.

Keywords: theory of constraints, drum-buffer-rope, protective capacity, make-to-order, capacity buffer

1. - INTRODUCTION

This study aims to analyse the impact of protective capacity on the implementation of the third step of the theory of constraints (TOC) drum-buffer-rope (DBR) methodology (subordinate everything to the bottleneck [BN] in make-to-order [MTO] environments). This study falls within the research line of Orue et al. and represents the 4th case.

For this purpose, a discrete event simulation is performed. The designed simulation is based on a case study in which Lizarralde et al. applied the systematic process of implementing the first two TOC-DBR steps, which will be presented in the Introduction.

The TOC is a management methodology based on the main idea that every system has at least one constraint that limits its performance. This constraint is the basis that is used to manage and improve a system [1]. The methodology's continuous improvement process consists of five steps: (1) identify the BN, (2) decide how to exploit the BN, (3) subordinate everything to a second decision, (4) elevate the BN and (5) return to Step 1 if the BN has been changed.

Within his line of research [2]–[4], Lizarralde provided a strategic perspective for the selection and exploitation of BNs in MTO environments. The researchers developed a systematic implementation process that consists of a set of four steps to identify and decide how to exploit the BN (Figure 1).

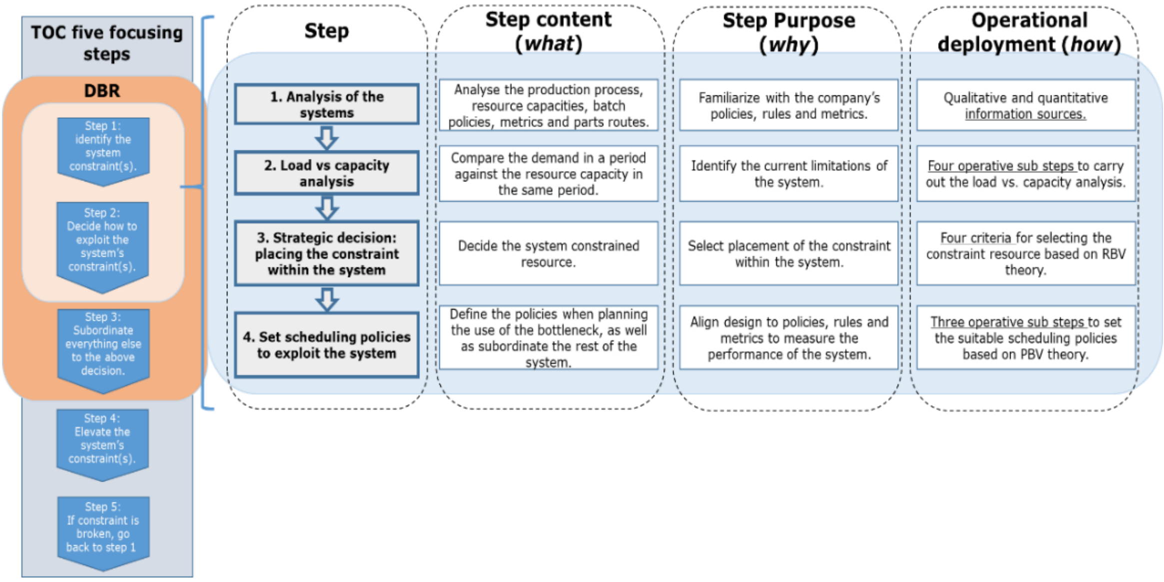

Figure 1. Systematic process for TOC Steps 1 and 2 [4]

As shown in Figure 2, sub-steps on how to operationally deploy Steps 2, 3 and 4 were also included.

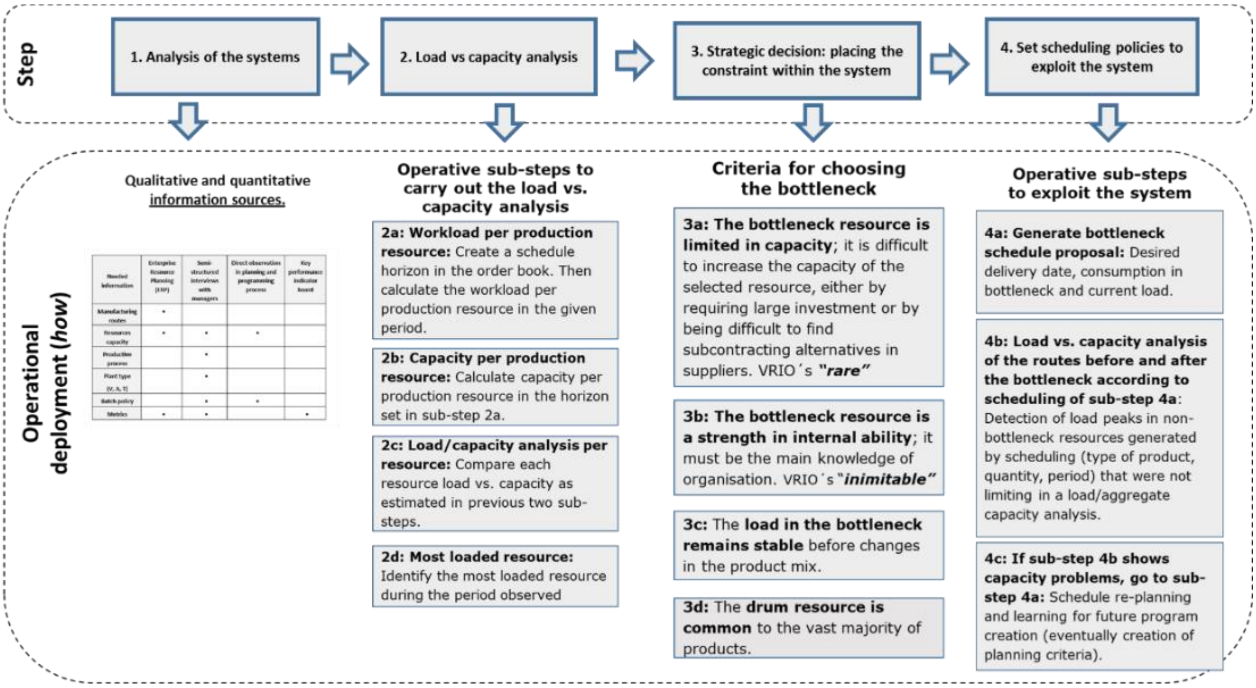

Figure 2. Systematic process steps, including operational deployment sub-steps [3]

To continue with the implementation process initiated by Lizarralde et al. [4], it is necessary to understand the impact of the protective capacity factor involved in the third TOC-DBR step in MTO environments.

The characteristics of manufacturing environments differ depending on whether the manufacturing is based on expected demand or whether the manufacturing is directly based on customer orders. In the literature, the former manufacturing environment and the latter manufacturing environment are also referred to as make-to-stock (MTS) and MTO, respectively [5].

In MTO environments, production or design starts after the order is received. They are dynamic environments by nature and customers can change, cancel or add orders during the planning horizon [6]. Consequently, MTO companies cannot accurately predict demand. For this reason, they cannot order materials and produce in advance or effectively implement batch production methods. In addition, the material and production requirements of a job can differ substantially from those of other jobs due to a lack of common parts and variable work routes [7].

Amaro et al. [8] classified MTO companies into two types: repeat business customizers (RBC) and versatile manufacturing companies (VMC). In RBC, products are customised and can be produced more than once, allowing for a small degree of predictability. In the VMC environment, it is more complicated to have some predictability, as an order is individually processed with a large variety of products and a variable demand that is produced in small batches with minimal repetition. Both RBC and VMC allow for customisation, but RBC is more stable, ensuring greater stability by drawing customers into a more predictable and committed relationship. Figure 3 illustrates the positions of the RBC and VMC categories relative to the MTS category.

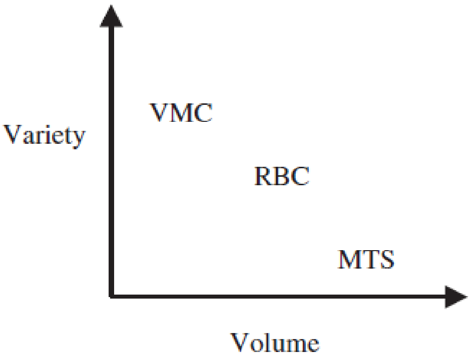

Figure 3. Classification based on volume vs. variety [7]

In response, this study uses discrete event simulation to address the following research question (RQ):

- How does the protective capacity of non-BN resources impact the results in MTO environments in which the DBR methodology is applied?

The article begins with a literature review in Section 2, in which the existing literature on Step 3 of the TOC is analysed, including the key factors involved and their impact on system performance. In Section 3, the discrete event simulation model employed to analyse the impact of protective capacity in implementing Step 3 of the TOC in MTO environments is described. Section 4 presents the results obtained in the experimentation that was carried out, followed by a discussion of these results in Section 5, in which the managerial implications are outlined. In Section 6, the conclusions are presented, followed by the limitations and future research options in Section 7.

2. – LITERATURE REVIEW

In conducting the TOC-DBR Step 3 literature review, it is important to define the key factors that impact a system when implementing the designed model. To understand this impact, in Section 2.1, TOC-DBR, Step 3 is defined. Section 2.2 identifies the key factors identified in the literature regarding subordinating a system to the BN. In Section 2.3, cases of implementation are analysed, with a focus on Step 3 TOC-DBR.

2.1 TOC-DBR STEP 3 DEFINITION

In Step 3, non-BN resources are managed to work in a way that supports the BN. These non-constraint resources have, by definition, more capacity than the constraint resource. The utilisation of this capacity margin will only produce work in progress (WIP), as the BN is not able to accept this excess work. Step 3 is only concerned with managing the utilisation levels of the non-BN resources and is determined by the capacity of the constraint but not by the potential capacities of the unconstrained resources [1].

2.2 KEY FACTORS IDENTIFICATION

As mentioned in Section 2.1, Step 3 of the TOC is concerned only with managing non-BN resources to support system constraints. This BN must be protected against variability and uncertainty affecting a system to ensure that the expected performance is achieved [9].

This variability in a system may prevent non-BN resources from feeding the BN resource even though the latter is available to work. This condition, which is referred to as constraint starvation, occurs when the material to be processed has not reached the BN resource [10]. Two key factors can be used to mitigate or eliminate this constraint starvation: protective capacity and protective inventory [11].

Protective capacity

To understand what protective capacity is, it is important to be familiar with a few basic terms. The two basic types of capacity are productive and idle, as seen in Figure 4.

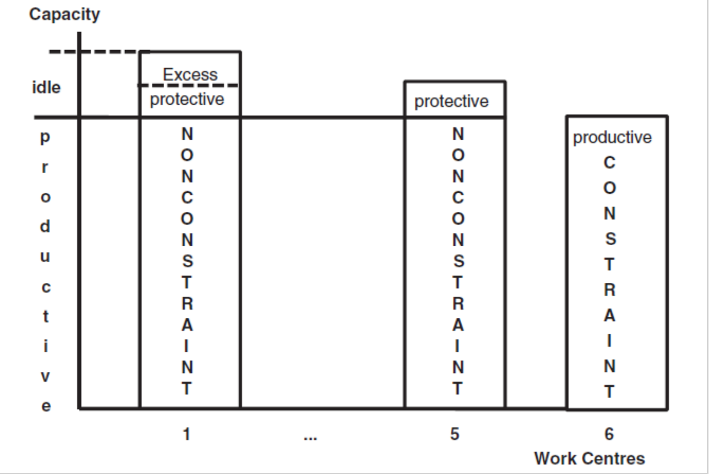

Figure 4. Productive and idle (protective and excess) capacities [11]

Productive capacity is defined as 'the maximum of the output capabilities of a resource (or series of resources)' [12, p. 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' [12, p. 83].

Protective capacity is defined as the 'resource capacity needed to protect the throughput of a system by ensuring that some capacity above the capacity required to exploit the constraint is available to catch up when disruptions inevitably occur' [12, p. 149]. Blackstone and Cox [10, 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 utilization of the constraint work station'.

Protective inventory

The same logic used to comprehend protective capacity will be applied to the protective inventory. The definitions and implications of inventory are similar to those of capacity [10].

Productive inventory is the amount of WIP inventory measured in time units required to meet the limitation until the material can pass from the first operation to the constraint [10].

'From a theory of constraints perspective, idle inventory generally consists of protective inventory and excess inventory' [12, p. 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' [12, p. 149].

2.3 INFLUENCE OF KEY FACTORS IN TOC-DBR STEP 3 IMPLEMENTATIONS

There is a variety of research that examines the influence of the key factors defined in Section 2.2 on system performance. Most of these works are simulations performed in different environments, and few focus on MTO environments. For example, Atwater and

Chakravorty [13] demonstrated the importance of protective capacity to achieve faster cycle times at lower inventory levels. Obviously, there is a cost associated with this protective capacity, so it is essential to determine the optimum level of this level of protection.

On the other hand, Caridi et al. [14] defined the important role of protective capacity in determining productivity. Lawrence and Buss [15] found that high levels of protective capacity decreased BN shiftiness at all BN utilisation levels. Other authors, such as Craighead et al. [16], confirmed earlier studies showing that the placement of protective capacity could reduce mean flow time.

In addition, Kadipasaoglu et al. [17] focused on the strategic use of protective capacity and its localization, assuring that it has a significant impact on shop performance. Orue et al. [18] demonstrated through a case study that the protective capacity of non-BN resources had to be higher in MTO scenarios than in MTS scenarios to ensure that the BN system would continue to be chosen.

Through a simulation experiment, Orue et al. (2021, in press) investigated the relationship between protective capacity and protective inventory in the implementation of Step 3 of TOC-DBR in MTS environments. They showed that the retention of the lowest level of protective inventory is a relevant factor in BN starvation if the protective capacity is lower than the system variability. If the protective capacity is equal to or greater than the system variability, the protective inventory does not affect the BN.

From the analysed studies, there is no doubt about the importance and necessity of protective capacity and protective inventory in the implementation of Step 3 of TOC-DBR. Taking into account these research areas and the objective of the study, the following section defines the research methodology to be followed.

3. – RESEARCH METHODOLOGY

It should be noted that this study is part of the line of research that Orue et al. are carrying out through simulation and is case number 4; the objective is the analysis and validation of the impact of protective capacity in MTO environments. Table 1 shows the studies that have been carried out and the main contributions of each study.

Company	Sector	Research strategy	Main contributions	Related publications
Case 1	High-precision machining company (MTO-VMC environment)	Case study	- Identify the two key factors defined by the literature in the execution of Step 3 of TOC, protective capacity and protective inventory - Identify through the case study that the protective capacity of non-BN resources is the key factor when subordinating the MTO system to a BN - Propose the critical phases of Step 3 of the systematic process	Published in the Journal of Industrial Engineering Management [18]
Case 2	High-precision machining company (adapted to MTS environment)	Case study validation through simulation	- Investigate and validate the relationship between protective capacity and protective inventory in the implementation of Step 3 of the TOC methodology in MTS environments	Conference proceedings from the XXV International Conference on Industrial Engineering and Industrial Management, Burgos, 2021
Case 3	Steel tubes manufacturing company (MTO-RBC environment)	Case study	- Designing the latest version of the systematic process for implementing Step 3 of the TOC methodology in MTO environments - Introduction of the capacity buffer concept in the TOC methodology - The proposed integration of the sales and operations process in the organisation through a systematic process	Conference proceedings from the XXVI International Conference on Industrial Engineering and Industrial Management, Toledo, 2022
Case 4	High-precision machining company (MTO-VMC environment)	Case study validation through simulation	- Analyse and validate the impact of protective capacity in the implementation of Step 3 of TOC methodology in MTO environments - Identify the use of protective capacity as a strategic decision of the company	

Table 1. Research cases

In addition, to have a global vision of the research, Figure 5 shows the research plan designed to systematise the implementation process of Step 3 of the TOC methodology.

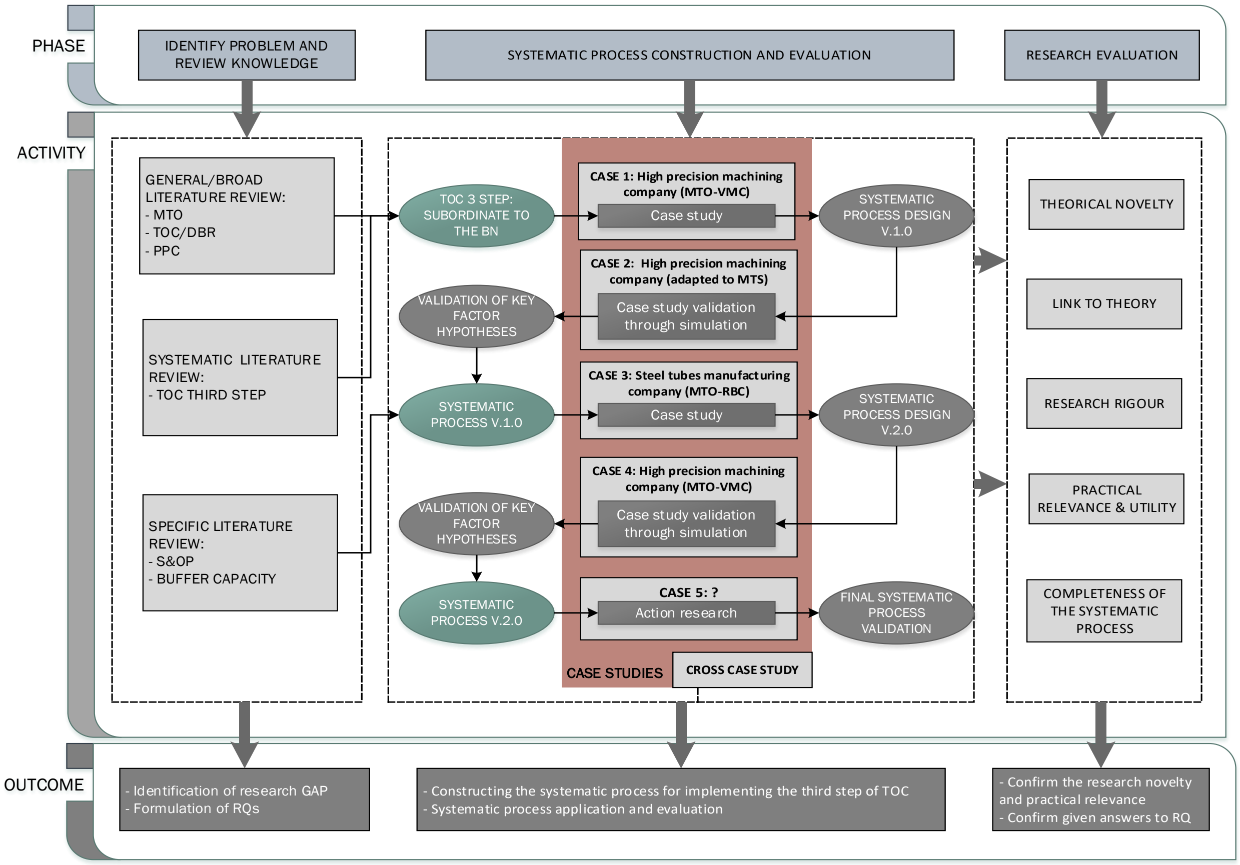

Figure 5. Research plan

3.1 SIMULATION MODEL

Section 3.1.1 describes the characteristics of the shop and workstation. In section 3.1.2, the assumptions that have been taken into account when modelling the system are outlined. Section 3.1.3 defines the experimental design and performance measures.

3.1.1 Job and shop characteristics

The designed simulation is based on a case study by [2], in which the systematic process of executing the first two steps of TOC-DBR was implemented.

Within the first step, identifying the BN, it was strategically decided that the fourth resource would be the BN. The reason for choosing this resource was that it was a difficult resource to imitate and that it was a key resource within the organisation’s knowledge. Once the BN was chosen, the next step was to decide how to exploit the limitations of the system. In this second step, it was decided to schedule the BN at 80% of its capacity due to the variability in defining the process time. Once the rules were decided, it was established that the objective was to meet the BN schedule above 99%. This objective would ensure a stable system that achieves the defined operational performance.

Taking this information into account, the system under analysis is a flow-shop workshop with six workstations, where all parts are processed at every single stage and share the very same route. The system, which was modelled with Simio software, operated according to specific assumptions to simulate its behaviour in different environments.

3.1.2 Simulation model assumptions

Regardless of the type of environment, we assume that the BN capacity is always 100 parts per hour and that this specific process has no variability. Taking into account that, in reality, the BN has variability, it is assumed that the objective is to meet the schedule defined in the BN and that the aforementioned variability is taken into account when defining the schedule. For this reason, variability can be assumed to be null.

Likewise, the breakdowns of the BN are assumed to be non-existent. Due to the critical nature of this process, redundancies, especially care, are taken so that this process practically never stops.

As previously discussed, MTS, RBC and VMC features vary in terms of product variability and order size. In practical terms, this variation implies that processing times are less predictable when moving from MTS to VMC (and RBC are somewhere in between).

Therefore, to evaluate the role of protective capacity within the different environments (MTS, RBC and VMC), these environments have been modelled in terms of the variability in the process durations different from 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: $[\frac{60}{C_P} \times \left(1 - V_p\right), \frac{60}{C_P} \times \left(1 + V_p\right)]$.

Regarding the protective capacity of the system, the capacity for processes different from the BN may vary in steps of size 10. Obviously, values should be larger than 100 (110, 120, etc.). The protective capacity exceeds 100 for non-BN processes. We assume that the capacity is the same for all non-BN processes.

Regarding protective inventory, the base scenario consists (minimum inventory) of keeping the number of parts prior to the BN equal to the number of parts that those processes can be processing at a given time with no extra inventory. Any amount above this value represents additional inventory that can compensate for the variability in the system and that can contribute to increasing the BN utilization rate but is not usable in MTO environments, as it is not known in advance what will be produced.

For a given value for the maximum parts upstream of the BN, we assume that the initial number of parts is equal to this number. As soon as parts are sent to the BN, numerous new parts are introduced into the system so that the inventory before the BN is the maximum inventory allowed.

Regardless of the environment, we also modelled some additional sources of unavailability of processing capacity due to breakdowns and repair times. Both the mean time between two failures (MTBF) and the mean time to repair (MTTR) follow exponential distributions. The MTBF is 100 minutes, and the MTTR is calculated so that the total unavailable time due to repair time is 0.5%.

Transfer times and setup times are not explicitly modelled and are implicitly computed within the capacity and variability of the processes.

3.1.3 Experimental design and performance measures

Experimentation consists of measuring the protective capacity required on non-BN resources to ensure that the BN utilization rate exceeds 99% (specifically between 99% and 99.4%). Protective capacity is assumed to be a multiple of 10 (0%, 10%, 20%, …).

To carry out the experimentation, the experimental factors detailed in *Table 2* are used. Once all the factors have been combined with all the levels, the values of the protective capacity necessary for the BN to work above 99% have been collected.

As mentioned in the previous section, it is very important that the protective inventory be minimal so that it is not the factor that absorbs the variability of the system.

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, 50
MTBF	100
Unavailability	0.5%

Table 2 Summary of experimental factors

4. – RESULTS

To analyse the total results of the experiment, two different methods have been utilised. Figure 6 shows the relationship between protective capacity and system variability. The protective capacity levels are obtained through the arithmetic mean of the starvation in the BN. In other words, five experimental replications have been carried out, and the necessary levels of protective capacity have been sought so that the average starvation in the BN is below 1%. This approach ensures that the BN programme is fulfilled above 99%.

On the other hand, Figure 7 also shows the relationship between protective capacity and environmental variability, but the results are obtained in a different way. It has been defined that starvation must be between 0.6% and 1% to ensure compliance with the BN schedule and that all levels of protective capacity that meet this requirement have been sought. Once all levels have been defined, the arithmetic mean has been employed.

Figure 8 shows the confidence intervals for each factor tested with a confidence level of 95%.

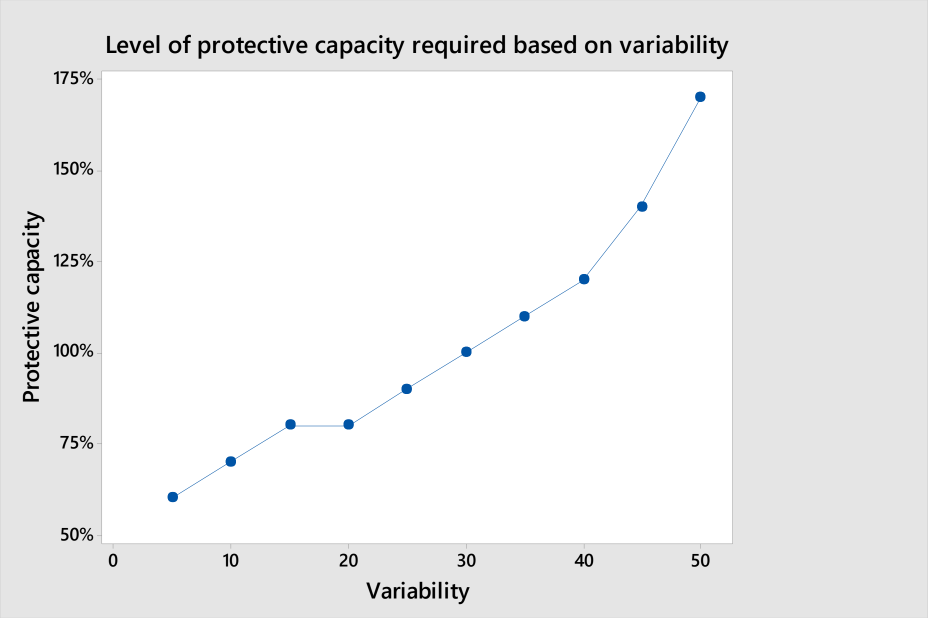

Figure 6. Relationship between protective capacity and variability (powered by Minitab software)

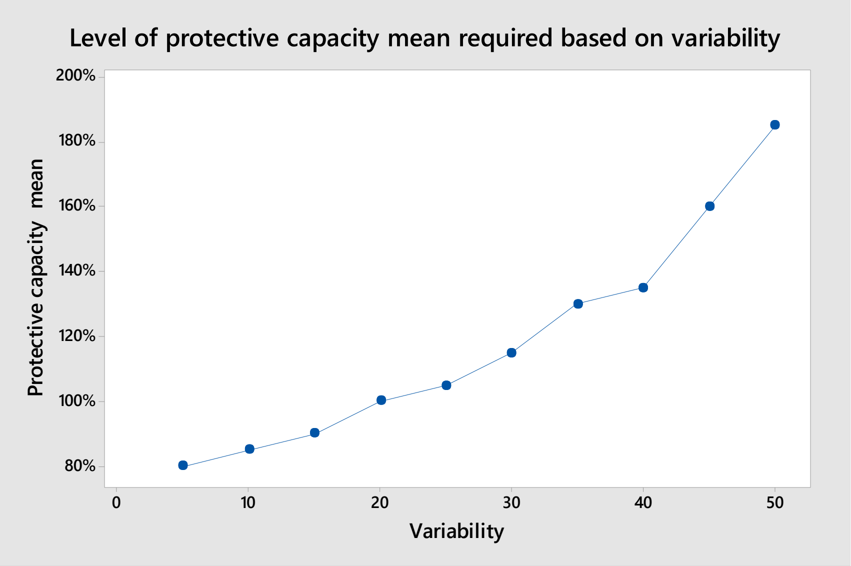

Figure 7. Relationship between protective capacity and variability (powered by Minitab software)

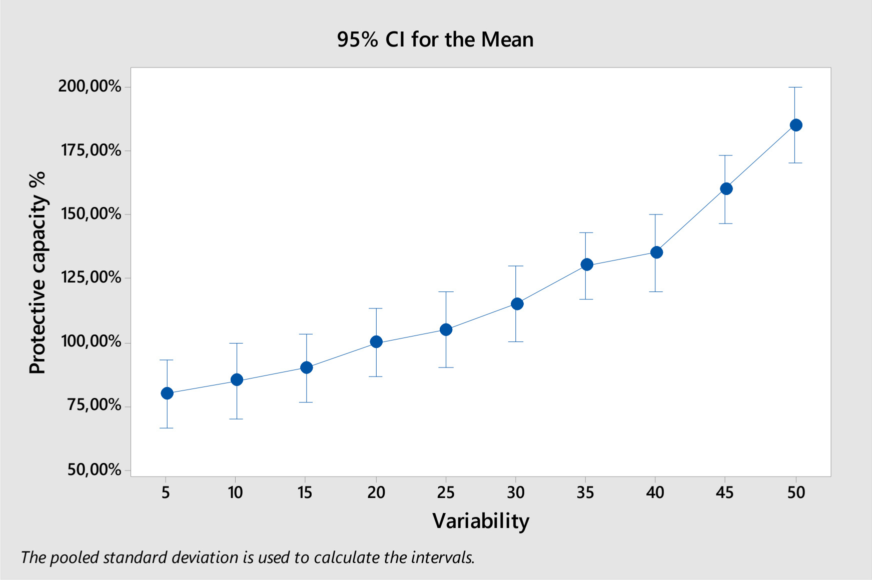

Figure 8. Confidence intervals with a 95% confidence level (powered by Minitab software)

4.1 PROTECTIVE CAPACITY ANALYSIS

To analyse the impact of the variability in the system with respect to the percentage of the non-BN resource protective capacity level, a statistical analysis of variance (ANOVA) was performed. Table 3 shows the results of the ANOVA.

To determine if any of the differences between the means are statistically significant, the p-value should be compared with the significance level (0.05 in this study) to evaluate the null hypothesis. The null hypothesis indicates that the population means are all equal. If the p-value is less than or equal to the significance level (0 in this study), you reject the null hypothesis and conclude that not all population means are equal.

To determine the possibility of significant differences between the means of the protective capacity factors, Tukey's pairwise comparison post hoc test was performed.

Table 4 shows the results of Tukey's test with a 95% confidence interval. If the interval in the "95% CI" column includes zero, the differences in performance are not considered statistically significant. Therefore, it can be concluded that if the interval does not include zero, the populations of the variability levels are different. It can be seen that at different levels of system variability, different levels of protective capacity are needed. These different levels could be divided into three, as the populations of the protective capacity are different from each other.

- The needed protective capacity differs between the system variabilities of 5%–10%–15% and the system variabilities above 35%.
- The needed protective capacity is different between the system variabilities of 20%–25%–30% and the system variabilities above 45%.
- The required protective capacities differ between the system variabilities of 30%–40%–45% and the system variabilities above 50%.

ANOVA (significance level α = 0.05)	DF	Adj SS	Adj MS	*F*-value	*p*-value
Variability	9	4.6478	0.51642	24.10	0.000
Error	35	0.7500	0.02143		
Total	44	5.3978			

Table 3 Results of ANOVA regarding protective capacity

Difference of levels of variability	Difference of means	SE of difference	95% CI	T-value	Adjusted p-value
10-5	0.05	0.0982	(-0.2815; 0.3812)	0.51	1.00
15-5	0.1	0.0926	(-0.2123; 0.4123	1.08	0.984
20-5	0.2	0.0926	(-0.1123; 0.5123)	2.16	0.501
25-5	0.25	0.0982	(-0.0812; 0.5812)	2.55	0.281
30-5	0.35	0.0982	(0.0188; 0.6812)	3.56	0.032
35-5	0.5	0.0926	(0.1877; 0.8123)	5.40	0.000
40-5	0.55	0.0982	(0.2188; 0.8812)	5.60	0.000
45-5	0.8	0.0926	(0.4877; 1.1123)	8.64	0.000
50-5	1.05	0.0982	(0.7188; 1.3812)	10.64	0.000
15-10	0.05	0.0982	(-0.2812; 0.3812)	0.51	1.000
20-10	0.15	0.0982	(-0.1812; 0.4812)	1.53	0.872
25-10	0.2	0.104	(-0.149; 0.549)	1.93	0.648
30-10	0.3	0.104	(-0.049; 0.649)	2.90	0.144
35-10	0.45	0.0982	(0.1188; 0.7812)	4.58	0.002
40-10	0.5	0.104	(0.151; 0.849)	4.83	0.001
45-10	0.75	0.0982	(0.4188; 1.0812)	7.64	0.000
50-10	1	0.104	(0.651; 1.349)	9.66	0.000
20-15	0.1	0.0926	(-0.2123; 0.4123)	1.08	0.984
25-15	0.15	0.0982	(-0.1812; 0.4812)	1.53	0.872
30-15	0.25	0.0982	(-0.0812; 0.5812)	2.55	0.281
35-15	0.4	0.0926	(0.0877; 0.7123)	4.32	0.004
40-15	0.45	0.0982	(0.1188; 0.7812)	4.58	0.002
45-15	0.7	0.0926	(0.3877; 1.0123)	7.56	0.000
50-15	0.95	0.0982	(0.6188; 1.2812)	9.67	0.000

25-20	0.05	0.0982	(-0.2812; 0.3812)	0.51	1.000
30-20	0.15	0.0982	(-0.1812; 0.4812)	1.53	0.872
35-20	0.3	0.0926	(-0.0123; 0.6123)	3.24	0.069
40-20	0.35	0.0982	(0.0188; 0.6812)	3.56	0.032
45-20	0.6	0.0926	(0.2877; 0.9123)	6.48	0.000
50-20	0.85	0.0982	(0.5188; 1.1812)	8.66	0.000
30-25	0.1	0.104	(-0.249; 0.449)	0.97	0.992
35-25	0.25	0.0982	(-0.0812; 0.5812)	2.55	0.281
40-25	0.3	0.104	(-0.048; 0.649)	2.90	0.144
45-25	0.55	0.0982	(0.2188; 0.8812)	5.60	0.000
50-25	0.8	0.104	(0.451; 1.149)	7.73	0.000
35-30	0.15	0.0982	(-0.1812; 0.4812)	1.53	0.872
40-30	0.2	0.104	(-0.149; 0.549)	1.93	0.648
45-30	0.45	0.0982	(0.1188; 0.7812)	4.58	0.002
50-30	0.7	0.104	(0.351; 1.049)	6.76	0.000
40-35	0.05	0.0982	(-0.2812; 0.3812)	0.51	1.000
45-35	0.3	0.0926	(-0.0123; 0.6123)	3.24	0.069
50-35	0.55	0.0982	(0.2188; 0.8812)	5.60	0.000
45-40	0.25	0.0982	(-0.0812; 0.5812)	2.55	0.281
50-40	0.5	0.104	(0.151; 0.849)	4.83	0.001
50-45	0.25	0.0982	(-0.012; 0.5812)	2.55	0.281

Table 4 Tukey simultaneous tests for differences of means

In the previous section, the results obtained through experimentation are presented. The following section discusses the main contributions of this study.

5.1 RESEARCH IMPLICATIONS

The following research question is posed in this study: How does the protective capacity of non-BN resources impact the results in MTO environments in which the DBR methodology is applied?

Using discrete event simulation based on a case study, it has been shown that at different levels of variability, different levels of protective capacity are needed to keep the system stable and to ensure that the BN schedule is met. The higher the variability, the higher the level of protection needed. However, the level of protection does not grow in a proportional way but has an exponential tendency to exist at the end of the curve. The key question is how much protective capacity is needed to absorb the variability?

As defined by Tu et al. [20], it is very difficult to determine the correct protective capacity. As Blackstone and Cox [10] pointed out, there is no mathematical approach to define the protective capacity level and it is very difficult to define the “adequate” protective capacity level.

This study also corroborates the point made by previous researchers that in a system with a defined variability, different levels of protective capacity can be employed to ensure a stable system but only if the level of protective capacity is sufficient enough to absorb the variability.

5.2 MANAGERIAL IMPLICATIONS

As previously discussed, it is clear that defining the level of protective capacity in MTO environments has direct implications for the people who will implement Step 3 of the TOC-DBR methodology.

As discussed in Section 1, the Introduction, MTO environments are more variable and unpredictable than MTS environments – that is, the levels of the BN protection against system variability must be higher. In addition, within MTO environments, there are two types of companies: RBC and VMC. VMC environments have the highest variability, as they are fully customised products with minimal or no repetition. The latter characteristic is so critical that a key factor in absorbing variability, such as a protective inventory, is not useful. In an environment where you do not know in advance what a customer is going to order, when they only order a few units, it is impossible to have sufficient inventory to absorb the variability in the system. In RBC companies, although the variability is lower than that in VMC companies, it could be argued that the protective capacity factor is also more important than the protective inventory. Customisation is still too high and batch sizes are still too small to be able to produce inventory in advance.

In summary, it can be said that the definition of the protective capacity level is a strategic factor when implementing Step 3 of the TOC-DBR methodology. Managers of a company working in MTO environments must fully understand that protection against variability must be non-negotiable if the BN schedule is to be met and if a stable system is to be maintained. The pursuit of efficiency in a non-BN resource whose function is to protect against variability can generate insufficient protective capacity and create starvation at the BN. Therefore, it is better to hedge and adjust the level of protection until an “adequate” level of protection is obtained. To accomplish this objective, it is advisable to monitor the consumption of protective capacity and adjust the level of protection. In the demand-driven adaptive enterprise model created by Ptak and Smith [21], the concept of capacity buffers helps manage this protective capacity. Capacity buffers reportedly protect control points and decoupling points by giving upstream resources the available capacity to catch up with system variability. Thus, a capacity buffer is a protective capacity that provides agility and flexibility [21, p. 72].

6. – CONCLUSION

According to the literature, protective capacity and protective inventory are key factors in the implementation of Step 3 of the TOC–DBR. However, protective inventory in MTO environments is not applicable due to the high level of order customisation and low repeatability of orders. To continue Lizarralde et al.’s research by designing a systematic implementation process for system subordination to the BN, it was important to understand the impact of protective capacity in MTO environments. This study has presented a discrete event simulation based on a case study.

The results show that for the BN schedule to be met above 99%, the higher the variability, the higher the levels of protective capacity required. Furthermore, the increase in variability and the level of protective capacity required do not increase proportionally, since at the end of the curve, there is an exponential trend.

It is important to note that the objective of the study was not to mathematically quantify the exact level of protection needed to absorb system variability but to analyse the impact of protective capacity in MTO environments.

As a final conclusion, taking into account the results of the study, it can be concluded that the definition of the level of protective capacity required is a strategic decision for the organisation. In the face of high levels of variability in the system, the protective capacity must be very high, which contradicts the vision of the efficient use of resources (that all machines are working at 100% of their capacity).

In order for managers to know and control how much protection is necessary and how much is overcapacity or waste, monitoring and managing the use of protective capacity is paramount. This concept of protection monitoring and control is relatively new to the TOC-DBR methodology, but it is applied in the demand-driven adaptive business model [21] and, therefore, can be concluded from this study with the need to integrate into the TOC-DBR methodology.

For a system to achieve the planned results, the system must be stable, which can only be achieved with a sufficient protective capacity on non-BN resources.

7. – LIMITATIONS AND FUTURE RESEARCH

One of the main limitations of our study is that in simplifying the model, factors such as the BN and shipping buffer have been disregarded. Although it is believed that these factors do not affect the outcome or objective of the study, this issue is worth exploring. Furthermore, the concept of the capacity buffer should be integrated into the TOC-DBR methodology. Therefore, future research should take into account the insights gained from this study and continue improving the design of the implementation process of Step 3 of TOC-DBR. Furthermore, it would be advisable to test this process in a real company so that the results can be evaluated and, in the event of any errors, corrected.

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