The Implementation of Theory of Constraints (TOC) in a South African Mining Environment: A Case Study of a Continuously-run Concentrator Plant

Hilda Kundai Chikwanda, Ph.D.
Associate Professor, Department of Engineering and Technology Management,
University of Pretoria
Pretoria, South Africa
Hilda.chikwanda@up.ac.za

Sifiso Innocent Mntambo
Instrumentation Engineer (Process Plant)
Royal Bafokeng Platinum
South Africa
SifisoM01@bafokengplatinum.co.za

Abstract

While the Theory of Constraints (TOC) is a broadly recognized management notion and has become one of the most used solutions in manufacturing industries, its implementation in various industries still needs further research. This study explores TOC implementation in a minerals environment where there are mining and minerals extraction activities. An instrumental case study approach is used for this research. The paper aids in explaining the method of TOC implementation in a continuously run concentrator plant. The 5-focusing steps, as pioneered by Goldratt, are used to identify constraints that limit the performance of a concentrator plant. In place of applying only the sequential TOC approach, the study uses a combination of existing improvement techniques with TOC. The theory's intended impacts on different sections of the concentrator were detected.

Keywords
Theory of Constraints, Continuous Improvement, Thinking Process, Constraints and Bottleneck.

1. Introduction

Business organizations continually track and implement new management concepts as well as sprouting practices. While the Theory of Constraints (TOC) is no longer a new concept, up till now, it has not been extensively investigated by researchers, mainly with respect to its implementation characteristics. TOC attracts managers due to its simplicity and often does not require any added investment. It is a systematic method for improving manufacturing effectiveness focusing on identifying and removing constraints that limit throughput. TOC has a strong customer focus approach and thus capable of transforming organizations. The successful application of TOC tends to increase industrial capacity. The theory can be used in manufacturing and services industries as well as in various managerial areas, such as: project management, quality management, information systems and others. However, it is particularly prevalent in production planning. TOC operates according to the principle that says 'a chain is no stronger than its weakest link'.

Mining is an important part of the South African economy and has been a driver of much development of the country (Mutemeri and Petersen 2002). Until recently, it has been an essential pillar of strength for the South African economy. Mining has been on a gradual decline since the 2008 recession and the South African mining industry is yet to fully recover. This has been aggravated by the current global pandemic crisis and so many mining companies have moved to 'survival mode'. The South African energy supply uncertainties have caused further instabilities to this industry. Hence, now more than ever, the South African mining industry is under persistent pressure. Some of the previously thriving mining towns are slowly deteriorating such as Thabazimbi in the Limpopo province. The implications, of all this, include decline in profits, lower revenues, higher operational costs, retrenchments and zero expansions.

Like the rest of the mining industry, the organisation under study is also in a 'survival-mode' and in dire need for ideas and innovations to keep it afloat. It is for these reasons that the research is done at one of the platinum group metals (PGM) producers' concentrator plant. The concentrator plant operates 24 hours hours/day and 365 days a year and has a three-stage crushing process, three milling sections and a floatation section. It produces platinum concentrate as a final product.

There are not many studies that introduce TOC to the mining industry, this study uses TOC as an approach for managing operations in a continuously run concentrator plant in South Africa.

1.1 Objectives

The main objective of the study is to successfully implement TOC and its thinking processes as a way to improve the productivity. The other aim is to determine challenges that are met in the mining industry so as to offer direction along the theory (TOC) building reasoning. This research answers the question: How can TOC be successfully implemented in a continuously ran concentrator plant? The research results are aimed at contributing towards making the plant more efficient and more profitable and that improvements in this plant will lead to direct benefits to all stakeholders as well as have an impact on the society at large through job preservations.

2. Literature and Theoretical Review

The TOC concept was introduced by Eliyahu M. Goldratt in the 1980's through the book called, The Goal. The core logic behind this concept is that, any company has at least one constraint that prevents it from achieving its goal. These constraints need to be known and managed. According to Sheu and Ehie (2003), constraints are factors that impact on the performance of a system. These may be physical resources (including equipment operators) as well as policies. Identifying constraints early, will increase productivity and allow decision makers to control the flow of material to the market. In reality there is no business without a constraint. If ever such a business existed, then that business would make infinite revenues. The owners and workers of such a business are yet to be born!

TOC helps to give better clarity and focus by identifying true constraints and to spend less time collecting data and more time solving problems (Izmailov et al. 2016). The central idea of TOC is that the goal of any business is to make more money now as well as in the future (Goldratt and Cox 1984). TOC is a continuous improvement process. It was developed to demonstrate how to effectively manage organizations and is based on two assumptions: (1) systems thinking, and (2) constraint management (Intelligent Management 2021). The basic TOC cycle consists of the five steps of improvement. These steps are (Dettmer 1998): (i) identify the bottleneck (constraint), (ii) decide how to exploit the identified bottleneck, (iii) subordinate everything else in the system to unblock the bottleneck, (iv) elevate the bottleneck, and (v) monitor if the bottleneck has been broken and return to the beginning (Goldratt and Cox 1992). Some researchers add a remark to the fifth step to avoid inertia while following other bottlenecks (Aguilar-Escobar et al 2016).

TOC is a philosophy that identifies that the whole is much more than the sum of its parts and that an intricate web of inter-relationships exists within the system. Mabin and Balderstone (2003), mention that the TOC approach exemplifies systems thinking. Its successful implementation uses a set of tools that guide users to find answers to basic questions relating to the sequence of change, namely: What to change? – looking for the constraint, What to change to? -defining how to exploit the constraint and How to cause the change? - management of the change (Goldratt 1990 and Dettmer 1998). TOC provides practical methods of managing the fundamentals for a successful change. Mabin, et al. (2001), state that TOC appreciates resistance as a necessary and positive element in a change process.
In spite of immense research experience, authors advise that there is still a need for further studies on TOC applications and application methodologies (Urban 2019). According to Gupta and Boyd (2008), TOC needs more experimental tests. In particular, TOC should be adapted to a wider variety of operational notions and matters. One of the leading techniques related to TOC is the Drum-Buffer-Rope method (Bhardwaj et al. 2010; Blackstone 2001; Golmohammadi 2015; Scheinkopf 1999). Non the less, many more methods are required, including real-world solutions backing up constraint identification and probing for suitable solutions for significant bottlenecks (Blackstone 2001). There are

two important measures used to quantify the performance of TOC: Financial (net profit, return on investment and cash flow) and Operational (throughput, inventory and operating expenses) (Pandit and Naik 2006).

A number of studies have been conducted in the past on application, limitations, and beneficial uses of TOC. The main emphasis is on continuous improvement which in turn results in improved organizational performance. While the TOC concept is comparatively simple and straightforward, the application of this idea is not easy or simple (Pegels and Watrous 2005). Even though TOC has been applied to other areas, such as performance measures, supply chains, marketing, and sales, it is mostly associated with manufacturing (Blackstone 2001). Literature also adjusts the elementary TOC methodology to be broader than the organizational and system levels, such as the sectoral level (Oglethorpe and Heron 2013).

Cases in which companies have accomplished operational excellence by means of focused process improvement and effective management and scheduling of constraint resources have been reported in books and academic journals (Cox & Spencer, 1998, Spencer, 2000, Kendall, 1998, Noreen et al.1995, Womack & Flowers, 1999). Later on, research on applications of TOC also shows benefits of operational excellence. Numerous manuals on TOC application are available (Cox & Schleier, 2010), however, there is still a deficiency of experimental research on the practical matters of TOC implementation in manufacturing systems. Applications of TOC in the service sector are relatively restricted (Ramasu et al. 2017). CCCC

The most noteworthy benefit of TOC implementation is the improvement in organisation's reaction to changes in the marketplace and hence gaining a competitive advantage. The main benefits are: i) Reduction in product cost as a result of the drop in manufacturing cycle time, lessening of waste, declining of inventories and the elimination of non-value-adding operations; ii) Improvement of quality; iii) Productivity improvement and iv) increased flexibility (Pandit and Naik 2006). Mabin and Balderstone (2000), concluded that on average, inventories in various industries such as automotive, semiconductor, furniture and clothing were reduced by 49%, production times measured in terms of lead-times, cycle times or due date performance improved by over 60%, and financial performance also improved by over 60%. Fogarty et al. 1991 agrees that TOC gives superior performance with significantly less effort.

3. Research Approach

A case study approach was taken to study the application of TOC in a continuously run concentrator at a mine in South Africa. The concentrator characteristics were provided. A case study method is used here as the study is focused on discovering how TOC can be implemented and how it impacts on the concentrator performance. An instrumental case study is employed as it offers insight into an issue or helps to refine a theory. The aim was to integrate; the application of the TOC's thinking process; application of Five TOC Focusing Steps; evaluation of the impact of the TOC implementation on the concentrator's throughput finally, running the same at a different but similar plant. TOC methodology is employed to identify and properly manage limitations known as constraints or 'bottle-necks'. It focuses on five identified production lines as elaborated in the next section. There is one product that is introduced into the concentrator (i.e. raw ore from the mine) and two products are produced i.e. the final concentrate and the tailings (which is a by-product).

Numerous data sources are used in this study (Yin 2009; Stake 1995). namely, the observation of the production process and the flow of the material throughout the entire system; real-time data from the existing plant interventions; the historical records of process features; direct interviews with managers, supervisors and operators; and finally, unstructured interviews with managers, supervisors and operators as well as observations during each visit. The findings and solutions that were determined are systematically compared with managers' views, proposals, and opinions. The results and the applied concepts are described in the following sections of the study

4. The concentrator plant: - the production system

The studied concentrator system provides platinum group metals (PGMs) concentrate as a final product. The concentrator plant operates 24 hours hours/day and 365 days a year. The identified production lines are: i) the crusher plant (where ore is received); ii) the milling sections (where grinding of the ore is done); iii) floatation (where valuable products are recovered); iv) filtration (where the final product is recovered) and v) the tailings plant (where the by-products are managed. The mine that provides the ore to the platinum concentrator (beneficiation plant) has three shafts. The ore from the mine is stored at a stockpile area, from where it is fed into the concentrator plant through the crusher plant.

The selected production lines have direct impact on the throughput. Ore rocks are crushed from 300mm to 10mm. The jaw crusher handles feed close to a 1000 tons per hour and so has impact on the throughput. The crushed ore is fed into silos and then fed into the milling section (primary, secondary and fine grinding) or further grinding. The output product is sent to the cyclones and then to the next stage of floatation. After passing through a number of floatation cells the processed ore goes to the next stage of filtration and is then treated as a final sellable product. The concentrator had a recovery of 87%. Figure 1 shows the flow process.

Figure 1. Concentrator Process flow

TOC methodology is used to identify and properly manage constraints or 'bottle-necks'. No new equipment or systems were bought thus no extra investment is required to implement TOC in this plant. Two stages are followed to implement TOC:

1) Application of the TOC's thinking process- to systematically identify the current state with respect to the production lines limitations. It helps to identify the root causes of the undesirable effects (UDE's) and helps to eliminate these without introducing new ones.
2) Application of TOC's 5-Focusing Steps- Identify that which limits the optimum running efficiency of the plant; Exploit using what can be controlled; Subordinate; Elevate; and Repeat/Inertia: - look for more constraints. This study had a special focus on the first step.

5. Results

5.1 TOC Thinking Process (TOC TP)

Existing continuous improvement techniques, namely, a combination of the Gemba Walks, Quick Kaizen, 5Ys and 5Ss were a part of the plant routines. Using the Gemba Walk technique, visits and interactions with personnel in the Crusher, Milling, Floatation, Re-Agent Area, Tailings Plant and the Filtration Plant sections established the current reality and the areas with challenges. The Gemba Walks were done only during the morning shift as this was the only practical time. To cover as many people as practically possible, the focus period was for 26 days. The distribution of plant challenges as reported by plant personnel is presented in Figure 2.

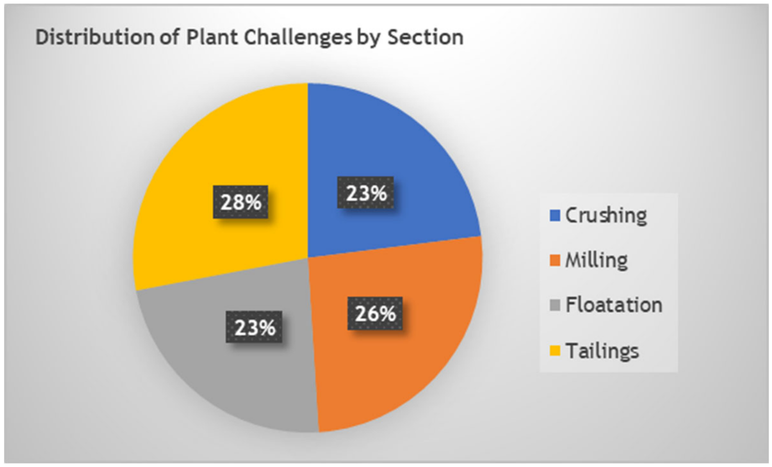

Figure 2. Distribution of plant challenges as reported by field personnel.

A summary of the specific areas of concern and possible causes is shown in Table 1.

Table 1. Identified challenges per Section

Section	**Challenges Identified**	**Possible Causes**
Crushers (Especially the tertiary crusher)	Trips on cone crushers Spillages Feed chocking Reduced crasher throughput Pump chokes	Oil leaks Pipe leaks Valve failures
Milling	Frequent trips Mill unavailability Overflowing of feed tank	Advanced Process Controller Cyclone pressure Lack of control Mass balance calculation Mill inlet density Flow (slurry) measurement Circulation valve status
Floatation	Lack of mineral recovery Pump failures Instrumentation failures	Search upstream flowmeters transmitters
Tailings management	Spillage	Search upstream

Stopped crusher means the feed from stockpile is affected while input into the mills is also affected as they may only run empty for less than 30 minutes. The floatation circuit may also be stopped affecting plant stability. Ultimately the recovery of PGMs is affected. Milling section has major impact on final product recovered from the floatation section. The floatation section is controlled by a combination of operator expertise and control systems.

Information generated during the TOC thinking process implementation together with the production data received between 2015 and 2018, were used for the next phase of using TOC's 5-focusing steps. The milling section was the first area of focus. Through a Quick Kaizen the focus was on the final mill with recurring trips. Proposed solution was to tweak the response time of the advanced process controller

5.2 Constraint identification

The improvement process in a system starts with recognizing where a bottleneck is in that system (Goldratt and Cox 1992). A bottleneck is a restriction of a system that controls the production flow. The constraint may be a physical one, such as a machine with a limited capacity or a raw material and may also be policy or behavioral constraints (Mabin and Balderstone 2003).

5.2.1 Inventory before a process as an indicator of a constraint.

The production flow in an industrial system is directly linked to the inventory or 'work in progress' that is waiting for successive processes. A high stock pile signals a bottleneck in front of the stock. Consequently, the bottleneck suggestively affects the waiting inventory. Production bottlenecks may be detected by noticing the buildup of inventories (Roser et al. 2015. Inventory can also be in form of material that is trapped in finished goods (Izmailov 2014). Inventory needs to be closely managed so that there is no oversupply of the final product and at the same time ensure there is no excess inventory along the production line.

The investigated plant keeps a huge stockpile of ore between the mine shafts and the crushers due to safety reasons. The other inventory along the production line is in form of spillages for various reasons including equipment failure. These too contain the sought-after minerals and so have impact on throughput of the plant. Inventories can accumulate anywhere along the value adding line shown in Figure 1.

From the studied data of measurements of the ore stock pile between the mine shaft and the crushers revealed that it is well managed. However, stoppages along the concentrator plant are abrupt and impact on both the ore stockpile on the surface and that underground. The data show predominantly high stock levels during stoppages on the milling section of the plant. Bottleneck identification according to inventories does not always give clear-cut results.

5.3 Tactics to exploit identified constraints

Once the constraint has been identified, the next step is to determine how to exploit it. From the understanding of the investigated plant, it is clear that there are many improvement options. Potential improvement options, hence need to be developed first prior to deciding on 'how?'. The focus is on increasing flow at the bottleneck as it is the determinant step of the throughput. Ordinarily, a simulation of the entire system is preferred. The increase in flow is linked to the step of subordinating everything else in the system to the constraint. When developing solutions for bottleneck exploitation, the increase in flow should be considered as early as possible.

5.3.1 Rapid increase in production capacity

Production capacity is a basis of customer response times, whereas, insufficient capacity is accountable for waiting times and unnecessary inventory levels (Rajagopalan and Yu 2001). Naturally and traditionally, managers tend to be quick to install new manufacturing units when there are capacity shortages in a process. Certainly, this decision gradually improves production capacity. The milling section, which has a direct impact on the recovery rate, can increase its productivity when a new unit is installed. However, it becomes clear that there is a new bottleneck in another section, the crusher section. This implies another investment in a new unit in this section, making it a costly exercise.

5.3.2 Continuous improvement process

Ordinary enhancements in the value-stream are a chant of Lean Manufacturing (Ohno 1988; Womack and Jones 2003). Every employee is encouraged to improve operations and machines on an everyday basis. The Lean approach reasons that at least one other plant is hidden as waste within a corporation (Womack and Jones 2003). This statement affirms of how much can be improved by Kaizen actions in a manufacturing system. It encourages the consideration of continuous improvement actions as a way to increase the flow through a bottleneck. Using what is known about processes of the concentrator sections, potential improvement in the bottleneck process were estimated. Figure 3 presents the monitored and measured KPI for two sections of the concentrator plant

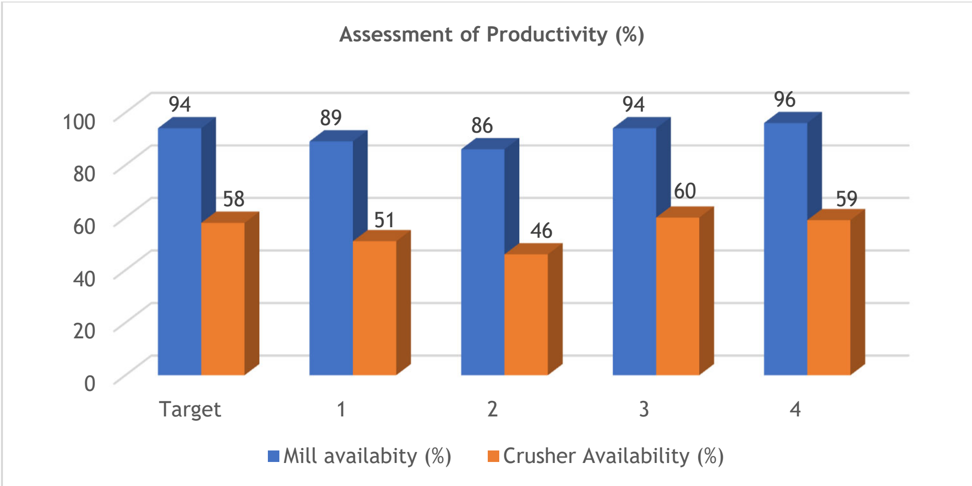

Figure 3. Tracked KPIs showing improvement with continuous improvement actions

Once the constraint was elevated at the milling section it moved to the crushing section and both sections' productivity improved, the aim was to maintain them and identify new constraints. It was clear that for the continuous improvement to be effective, there is need for strong determination of management as well as the operators. It must cover the whole production process and not only one section. During the entire experimental period, the recovery was targeted steadily at an average of 85.3 % against a target of 87 %. Furthermore, in all processes hence sections of the plant, any increase of throughput, in money or volume, benefits the company. Therefore, the calculation of the typical TOC measures was used in combination with other measures alleged as supportive for making improvement decisions. Table 2 below shows some of the monitored parameters that had impact on the plant

Table 2. Achieved productivity and availability improvements in a similar plant

Activity	**Action**	**Impact on plant**	**Measure**
Primary Mill Optimization	Collaborative effort from different departments to Maintain same or better recoveries	Improvement of 29,5 on throughput (production)	Productivity
Remote monitoring and support of primary pump: - Main cyclone feed pump drop in operating compliance	Backup pump testing and timely switching	Avoided the regular 2-12 hours of production loss	Availability
Rougher Floatation optimization	Investigate blower system and air flow points.	Improvement of mass pull and recoveries	Availability

6. Discussion

TOC has several measures including a) throughput in financial terms: (b) inventory in monetary terms, and (c) operating expenses (Goldratt and Cox 1992). These measures are alleged to be conflicting to those of the traditional accounting system that offers an international view of a company (Mabin and Balderstone 2003 and Mehra et al. 2005). The measures are aligned with the strategic objectives of the company (Draman et al. 2002 and Smith 2000). Regularly, these measures are practically used for optimisation of product mix (Alsmadi et al. 2014; Wojakowski 2016; Gupta et al. 2002). Such measures should be used for decisions that influence the organisation' s main goal (Goldratt and Cox 1992). The plant under study has only one product, platinum group metal (PGM). The plant operates continuously and its sections have to run concurrently. It is challenging to implement change on a continuously running plant, however, through well thought processes, it is possible to implement the TOC concepts. It is vital to make people part of the change that is required to be seen. People themselves, can be a big constraint. In a pressurised environment, such as in a continuous running plant, people resist change for fear of losing their jobs. They are happy to follow untested biased processes.

However, through engaging operators, plant overseers etc. and taking them through the change process as well as allowing them to voice their contributions through the changes, a buy in process is made easier. The ground team knows their sections, perhaps better than management and supervisors. They know what it would take to make their everyday task easier. If there are solutions to be implemented, the first people to consult are field operators themselves. The process allows for face-to-face interaction and minimal confrontations. Misconception are soon identified and an opportunity to correct these avails itself. The role of the supervisors and management is to filter the proposed solutions and manage those that have potential to add value. When responsible people are held accountable to implement the solutions, at the next available opportunity without disruptions to the running plant, they will succeed in changing the plant operation.

Engaging and holding discussions with operators, revealed that they had bias and preferences towards the machinery they use and were reluctant to change anything. Such bias and reluctance are instilled over long periods of time. Operators had fallen in some comfort zones. Fear kept many from trying new things, lest the expected improvements do not happen. Not much technical thought was put into the operating equipment and machinery. All they relied on was the 'reputation' of a certain equipment to perform. A typical example that was common in all the sections was the reluctancy to alternate pumps where there are two pumps for the same application i.e. spare pump. These need to alternate every seven (7 days in order to extend the life of both pumps. However, this study found that this hardly took place. Operators insisted on the pump that apparently gave better efficiency. Ironically, it is this kind of behaviour that compromised the efficiency of the entire system.

Importantly, the ground team needs to be aware of the targets that are expected of them, and how these fit in into the overall company's objectives and targets. A reward system where employees are rewarded for knowing and reaching their targets allows proposed solutions to be directed towards consistently meeting the targets.

This study of the concentrator plant shows that implementation of TOC in a continuously run plant is peculiar. With regards to bottleneck identification, a number of other tools can aid the TOC process. The Gemba Walk concept was quite useful and instrumental in effecting both the TOC thinking process and the 5-focus steps. The first part of constraint identification was at section level then the second part was within the section. Existing control systems were effectively used to gather information for measuring the plant performance. Due to the synchronization that needs to be between this concentrator plant and the mining activities, the downstream and upstream effects of every section had to be considered. To identify the real constraint in the different sections with different processes, engagement with staff was key. Although inventories are a good marker of bottlenecks in a system, it is rather challenging to use minerals inventories in form of spillages (Roser et al. 2015). Moreover, strategic inventory has to be stocked albeit at the right position within the value stream. A deep understanding of the production flow as well as the different forms of inventories is key. For this work the inventory was high before the crushers and yet the constraint was on the milling section. This shows that there are other factors that influence the identification of the constraint (Urban 2019). The issue of constraint identification is therefore, an important issue and every production process needs to the carefully studied for use of appropriate techniques and tools to be employed. Individual system characteristics and circumstances have to be considered so as to clearly identify the constraint.

Prior to exploitation of the bottleneck it is essential to have an extensive understanding of the production system. It is worth looking at both the improvements on the bottleneck as well as the 'next level' constraint. In this case it was not necessarily in the same section. It also appears as if exploiting one constraint after another may be slowing down the improvement process as other potential improvements can run concurrently. Just as the value stream under consideration here has some synergy with up- and down-stream processes, the exploitation of the bottleneck should also be in synergy with other improvements. Manufacturing and external constraints ought to be concurrently looked at, because, numerous answers should be jointly applied to the bottleneck problem (Pegels, and Watrous 2005).

The production case herein focuses on application of TOC to a concentrator plant which is a part of the bigger mining system. The first activities of the plant (the stockpile) depend on upstream actives of the mine. Insights of the upstream activities allow the concentrator plant activities to be planned and maintained. Therefore, two production systems at different levels belonging to one organization to impact on one organizational goal. According to TOC theory, at any given time there exists one constraint for the entire system. This study focused on a part of the system that is treated separately but has to be in sync with the mining activities. Within the plant are different sections that have different processes and produce a progressive product. Each is not looked at separately. The flow of the TOC implementation process is shown in Figure 4. The identification of the system constraint is in stages and it uses many different methods. It is preceded by the identification of all processes along the value chain and their characteristics. The engagement of each process is crucial. Each section should have an appropriate method to measure and identify the bottlenecks. Determination of the bottleneck is important as well as the estimation of flow limitations in other processes (next level constraints). It is important to know the different capacities among processes. A solution of how to increase flow through a bottleneck can be determined after understanding it with respect to capacity. However, not only capacity, but other processes need to be considered. Many solutions can be implemented and so there has to be an evaluation process to enable the making of reasonable choices by those accountable. The mix of improvement solutions should then be determined in line with production flow and productivity of the entire system. Ultimately, Throughput Accounting is a supportive methodology (Simatupang et al. 2004; Draman et al. 2002; Smith 2000). Other techniques in TOC may be implemented (such as Drum–Buffer–Rope, if inventory accumulation is to be avoided (Bhardwaj et al. 2010; Scheinkopf 1999).

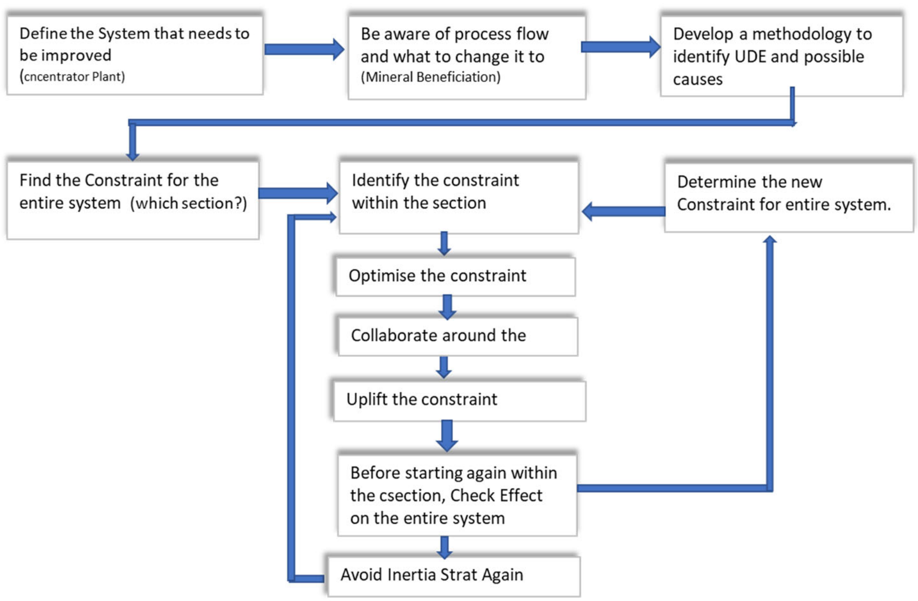

Figure 4. TOC Implementation flow for the concentrator Plant.

When the plan of improvement decision has been made, its implementation and monitoring follow. Always start with a renewed understanding of the existing constraint.

7. Conclusions

The study shows that the TOC 5-step method may not always be the best. These findings are in line with Pretorious (2014), who argues that its sequential nature is an important shortcoming on the implantation of TOC.

A thorough examination of the concentrator study reveals that there is a requirement for a different method when dealing with different environments. The most suitable outlined above is that constraints can be dealt with as a set. An improvement solution 'blend' that does not only focus on the bottleneck is required to meet a new level of productivity. Another requirement is inclusive understanding of the production flow in all processes and extra possible constraints. A blend of practical improvement solutions ought to be rationally chosen in view of several criteria within the business environment.

The production system studied has varied processes and so production processes require different capacities. This is a multi-dependent one. In order to control a bottleneck and to comprehend the different capacities between processes, process engagement is necessary.

The results show that the manufacturing system is extremely interconnected and exclusively intricate such that when applying TOC to it, a very adapted approach to bottleneck/ constraint identification and improvement strategy is needed. Gupta (2202), affirms that the real-world manufacturing environment is much more complex than that offered in literature. Accordingly, the bottleneck limitation and other probable restrictions should be jointly well-thought-out when defining the target productivity for a system improvement. This study contributes to production management theory by proposing an alternative way that reflects on variances in processes and capacity utilization when implementing TOC.

A successful implementation of TOC and its thinking processes as a way to improve the productivity had been shown. However, there are challenges that peculiar to the mining industry and an adjusted TOC implementation process flow has been proposed.

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Biographies

Hilda Kundai Chikwanda is an Associate Professor in the Faculty of Engineering, Built Environment &IT (EBIT)'s Graduate School of Technology Management (GSTM), at the University of Pretoria (UP) in South Africa. She is an established researcher and leads the GSTM's research work in operations management. Her background is in metallurgical engineering. Hilda is a chartered engineer and a fellow of the Institute of Materials, Minerals and Mining (IMO3). She has published extensively. She holds a PhD in Engineering from Imperial College in London and an MBA from the Gordon Institute of Business Sciences in Johannesburg.

Sifiso Mntambo is an Instrumentation Engineer. He has been in the trade for 20 years, specializing in the mining environment. He is currently employed at the Royal Bafokeng Platinum Mine. His biggest professional quest is to introduce, implement and manage exponential technologies within the mining sector. Sifiso is a firm believer in the empowerment of workers through enabling a platform where workers are introduced and skilled in the technologies of the future. He holds an MSc: Project Management (University of Pretoria), Honors Degree: Technology Management (University of Pretoria), B-Tech: Electrical Engineering [Instrumentation] (University of Johannesburg), National Diploma: Electrical Engineering. Sifiso is in his final year in pursuit of a Masters in Business Administration (MBA) degree with the University of Johannesburg. He is a member of the Engineering Council of South Africa (ECSA). Sifiso Mntambo is a family-oriented individual who owes his life inspiration to his wife Christina as well as his three daughters; Thandolwethu, Awande and Lubanzi.