A simulation-based system modelling approach combined with the theory of constraints steps in identifying and ranking constraints in production planning at Finsch Diamond Mine

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Finsch Diamond Mine (FDM) undertook an analytical study in 2018 followed by an optimisation study in 2019 as part of efforts to improve its production throughput. However, the two studies could not get the production cycle at FDM to reach the planned production throughput. Therefore, the study presented in this paper was undertaken to plan on how to holistically overcome the shortcomings of the two previous studies. The study used the Theory of Constraints (TOC) which is a management science methodology generally applied to improve production processes by eliminating production bottlenecks (or constraints). TOC is premised on five focusing steps. The first step on constraint identification is critical because incorrect constraint identification implies that successive steps are spent on resolving wrong production bottlenecks leading to envisaged production process improvement not being achieved. A simulation-based system modelling approach was used to identify and rank constraints in production planning at FDM. Simulation was selected because it is a non-disruptive cost-effective way of experimenting with complex systems such as production processes. By simultaneously reviewing a simulation model of the production process, analysing historical data, and engaging in qualitative discussions, enabled holistic identification of constraints (or parameters) with most impact on production throughput. The first step in the study included the preparation of data for use in a software program called Simio where discrete-event simulation experiments on the production cycle input parameters were run and compared to baseline values. The TOC methodology was then applied by assuming that each production cycle parameter might be a constraint, changing its value and measuring the consequent change in production throughput as part of the second and third steps of the TOC methodology. Once throughput was maximised for a constraint, the constraint became irrelevant, hence the next significant constraint would be identified, and the process restarted as steps four and five of the TOC methodology. The top ten significant constraints were identified and ranked using this system modelling approach and TOC methodology. These constraints were validated through reviews by the mine planning team and informed recommendations on improving the production cycle at FDM to assist in formulating future optimisation studies.

INTRODUCTION

Finsch Diamond Mine (FDM) is a sublevel caving (SLC) mining operation located in the Northern Cape province of South Africa and is owned by Petra Diamonds Ltd. Figure 1 illustrates the location of FDM.

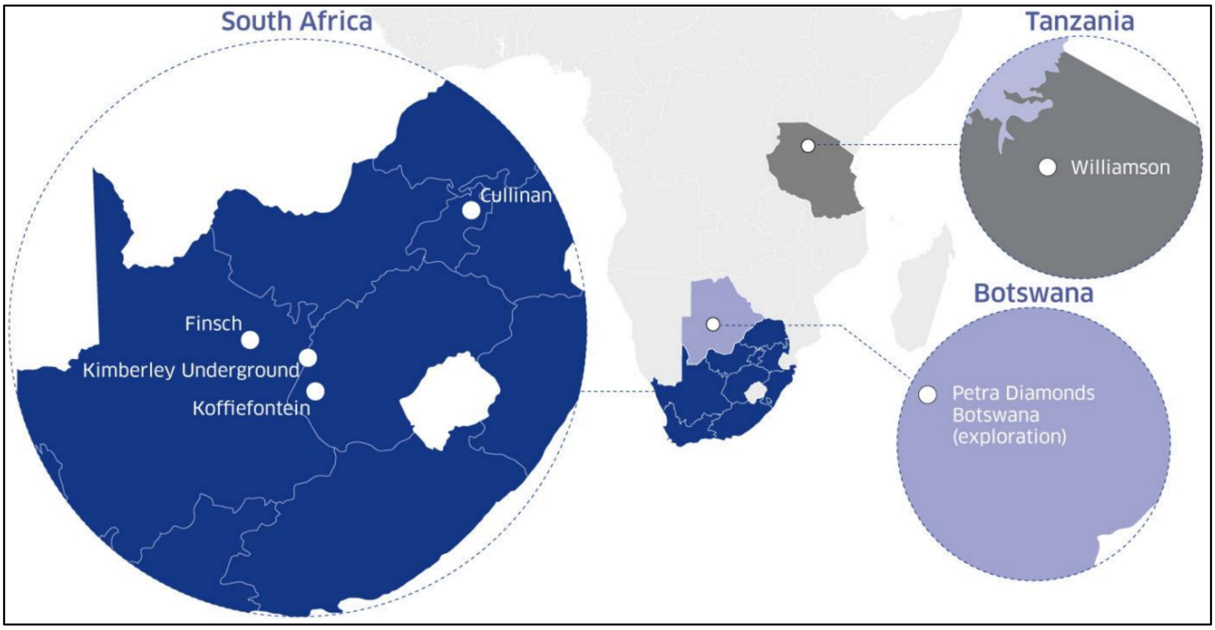

Figure 1. Location of Finsch Diamond Mine (Source: Petra Diamonds Ltd, 2015).

The production cycle at FDM comprises of a typical SLC operation. Between 2015 and 2017, FDM was experiencing challenges in achieving its planned run-of-mine (ROM) ore production throughput of 280,000 tpm. Consequently, it undertook an analytical study in 2018 followed by an optimisation study in 2019. These studies managed to improve the mine's production throughput but the production cycle at FDM failed to reach the planned production throughput.

The 2018 study focused on the efficiency of load-haul-dump (LHD) units and utilised real-time data from Sandvik's Optimine system. The data from the Sandvik Optimine system formed part of the baseline data (Table 1) used in the model calibration and simulations collected for the calibration of the simulation model in this paper. Besides the data from the Sandvik Optimine on loading, other data were extracted from the Epiroc Certiq system on drilling and the Ampla system on breakdowns and delays. Some of the historical data on delays which caused deviations from planned targets were drawn from the Ampla system included treating big rocks or hang-ups, installing safety nets, fixing roadways, fixing damaged ventilation pipes, and rehabilitating tunnel support. The study resulted in the ROM production throughput increasing to an average of 235,000 tpm between October 2018 and September 2019 (Figure 2). The 2019 study assessed the performance of all FDM mining activities and costs using a value driver tree analytical approach (Petra Diamonds Ltd, 2019). The study resulted in the ROM production throughput increasing to an average of 250,000 tpm between October 2019 and February 2020 (Figure 2).

Table I. Baseline input parameters used during the model calibration and simulations (Source: Oosthuizen, 2021)

Baseline Parameter	**Value**			**Unit**
Production	**Minimum**	**Average**	**Maximum**	
Scheduled production time		16.5		Hours
Overtime weekends		3		Weekends
Drill rigs in use	-	4	-	Machines
Drilling time (per ring)	18	-	24	Hours
Drill rig tramming speed		1.5		Km/h
Charging rigs in use	-	3	-	Machines
Charging rig setup time	20	25	30	Minutes
Charging time per ring	1	1.5	2	Hours
Charging rig tramming speed	-	3	-	Km/h
Loader, Hauler Dumper (LHD) in use	-	8	-	Machines
Allowed LHD - 70 Level		2		Machines
Allowed LHD - 73 Level		4		Machines
Allowed LHD - 75 Level		5		Machines
Allowed LHD - 78 Level		3		Machines
LHD load size (fill factor)	6	8.5	12	Tonne
LHD tramming speed (empty)		9		Km/h
LHD tramming speed (full)		6		Km/h
LHD fuel capacity	50	-	350	Litres
Probability of grid being unavailable		1 out of 15		Tips
Grid clean time	5		10	Minutes
Fixed rock breaker availability		85		Percent
The ground handling system's parameters will remain fixed during the study as it has the capacity to crush and convey up to 18 00 tonnes per day.				

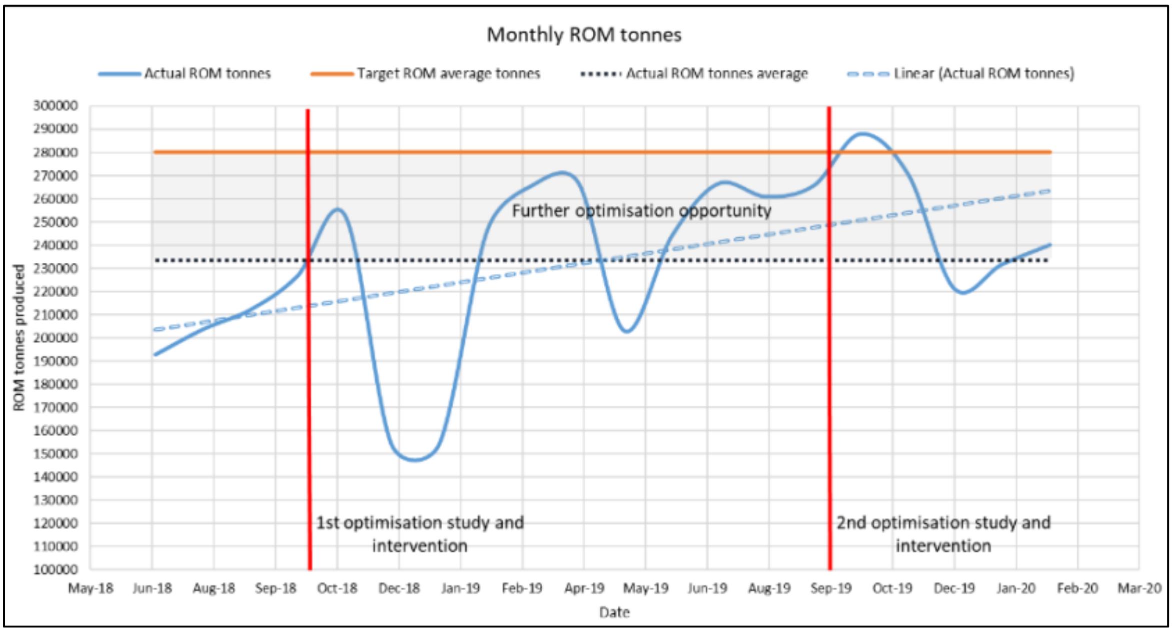

Figure 2. Monthly ROM production throughput trend at Finsch Diamond Mine from June 2018 to February 2020, indicating the impact of the two optimisation studies (Source: Oosthuizen, 2021).

Figure 2 indicates that although the two studies resulted in an increase in production throughput, the production cycle at FDM could not reach the planned production throughput of 280,000 tpm. Therefore, it was necessary to undertake a different study which could aid in holistically overcoming the shortcomings of the two previous studies. That study as presented in this paper used the Theory of Constraints (TOC), which is a management science methodology generally applied to improve production processes by eliminating production bottlenecks (or constraints).

TYPES OF CONSTRAINTS

A constraint is a bottleneck or restriction that limits a system's throughput, and in a mining context this could potentially lead to reduced cash flows. Therefore, it is important to identify, classify and resolve the constraints to enable the mining operation to generate more cash flows. In a mining production system, three types of constraints that affect throughput can be categorised into three main categories namely natural constraints, activity constraints, and process constraints. Natural constraints are physical factors like rock stress, humidity, heat, and the characteristics of the orebody. An example of the impact of natural constraints relevant to SLC mining in kimberlite rock formations is that drilling is typically restricted to a dry operation with dust control measures because kimberlite easily disintegrates in the presence of water. It is sometimes impossible or very expensive to mitigate some of these natural constraints (Morrison, *et al*., 2018). Activity constraints are derived factors related to the characteristics and execution of the production activities. Examples of activity constraints are performance-related measures, such as rate of advance, drilling rate, and speeds at which broken rock is loaded and trammed. Activities during the mining process can sometimes be very complex, often requiring considerable intervention from humans who must follow policies and procedures to avoid mismatches between sequential activities and safe execution of those activities. Process constraints are related to policies and procedures. An example of these constraints is the requirement to optimise ring drilling in a drift by drilling say four to six rings in advance, then blast about three of the pre-drilled rings at a time, but some of the longholes in a ring may require re-drilling due to blockages caused by the blasting. At FDM, production-end availability is one of the major issues and the source of the problem is process constraints in the system.

THE THEORY OF CONSTRAINTS

Goldratt (1990), a management science consultant articulated the TOC concept and its framework, which presumes that when an organisation or business wants to continuously improve the overall throughput of its production process, the following five focusing steps must be followed:

- Step 1 (Identify the most limiting aspect of the system, which is the most significant constraint currently limiting the production system from attaining 'the goal'). This most limiting constraint should be alleviated to operate at its maximum capacity, hence leading to Step 2.
- Step 2 (Exploit the constraint). This step entails firstly, an understanding the mechanism of the most limiting constraint to ensure its capacity is maximised to operate at 100%, hence ensuring the constraint is utilised to increase throughput.
- Step 3 (Subordinate everything else to the constraint). In this step, it is necessary to prioritise the management of the constraint so that other aspects of the system can provide the constraint with enough resources to fully utilise the constraint. The constraint should never be starved of inputs or resources, hence the need for Step 4.
- Step 4 (Elevate the constraint). Once the throughput at the constraint has been maximised, the resources required to keep the constraint fully utilised must be maintained to ensure the throughput of the system remains maximised. This may require purchasing of new equipment or hiring of additional staff. By ensuring the constraint can continue to operate at 100% capacity, it becomes irrelevant, hence the need for Step 5.
- Step 5 (Once the constraint becomes irrelevant, the next important constraint must be identified, and the process restarted). This step assumes that once a constraint has been elevated, the next ranked limiting constraint will emerge within the production system, hence the need to restart the process by going back to Step 1, hence achieving continuous improvement.

The above five focusing steps illustrate that the TOC methodology is iterative to ensure continuous improvement can be achieved. In this study, it was important to rank constraints to facilitate the execution of the TOC iterative steps. It is important to note that any effort spent in resolving subsequent constraints is a futile exercise unless the current constraint is correctly identified, resolved, and becomes irrelevant. Therefore, constraint identification is a critical step in the TOC methodology. In this study, constraint identification was done by simultaneously reviewing a simulation model of the production process, analysing historical data, and engaging in qualitative discussions. The production system can be characterised as a discrete sequence of events with each event occurring at a particular time and marking a change of state in the production system, hence a discrete-event simulation (DES) experimentation approach was appropriate. The production system modelling included the preparation of data for use in a software package called Simio (**Si**mulation **M**odelling framework based on **I**ntelligent **O**bjects) which enabled DES experiments on the production cycle input parameters to be run and outputs compared to baseline values.

PRODUCTION SYSTEM MODELLING IN SIMIO

Simio is an object-oriented DES software package designed to simulate complex systems with a view to enable graphical definitions of objects and processes as illustrated by the example in Figure 3. Therefore, Simio does not require complex end-user programming skills, but a good understanding of the system logic.

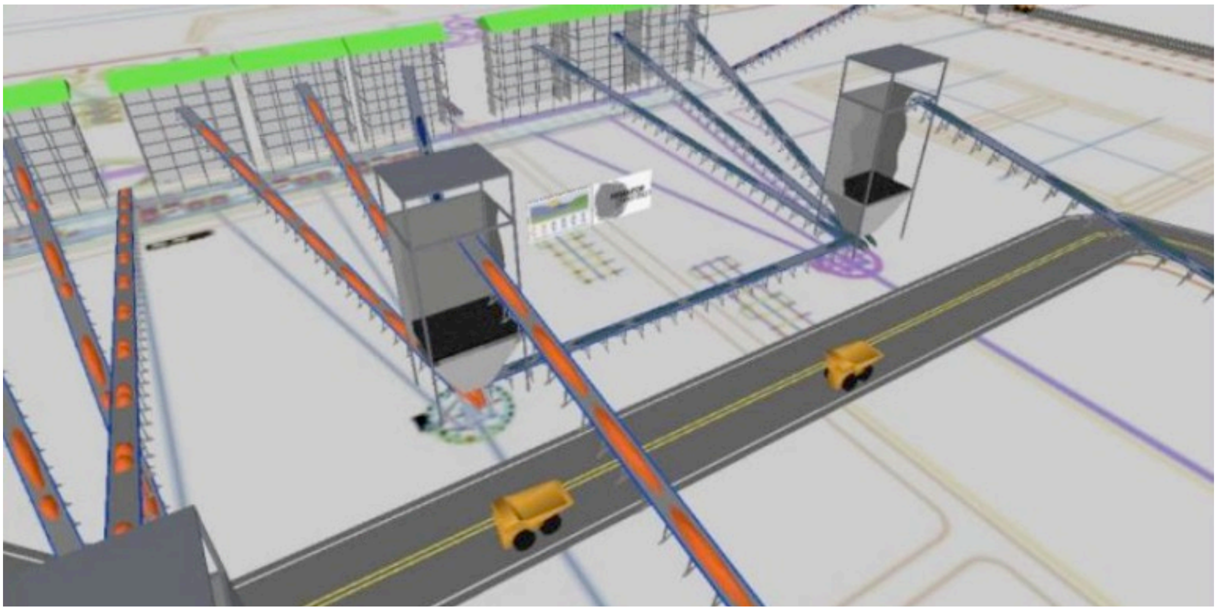

Figure 3. Simio model of a coal processing plant (Simio, 2020).

Simio can simulate the impact of changes to processes to improve the performance of processes by optimising the use of critical resources and identifying the best throughput options (Simio, 2020). It is possible to create a Digital Twin of a system in Simio. FDM contracted a company called Process Design and Automation in 2016 to build and calibrate a Simio simulation model of the mine's SLC operation. The model has been used in life-of-mine planning projects at FDM and generates reliable and realistic outputs from about 15 simulation runs or replications at a time. Therefore, this study used the Simio model of the SLC production cycle at FDM to run various production input parameter scenarios.

The Simio model is a spatial representation of the mine. In its development, a computer-aided design (CAD) drawing of the mine was imported into the model and correctly scaled, for example as depicted by the graphic of 75 Level illustrated in Figure 4. The CAD model was then fitted with various static and moveable objects representing the orebody, infrastructure and equipment used in the mine (Van

Huyssteen, 2019). Figure 5 depicts some of the graphical objects in Simio. The graphics in Figures 4 and 5 are examples of how operational and mine planning staff can visually observe and test the validity and practicality of the simulation in the real production environment.

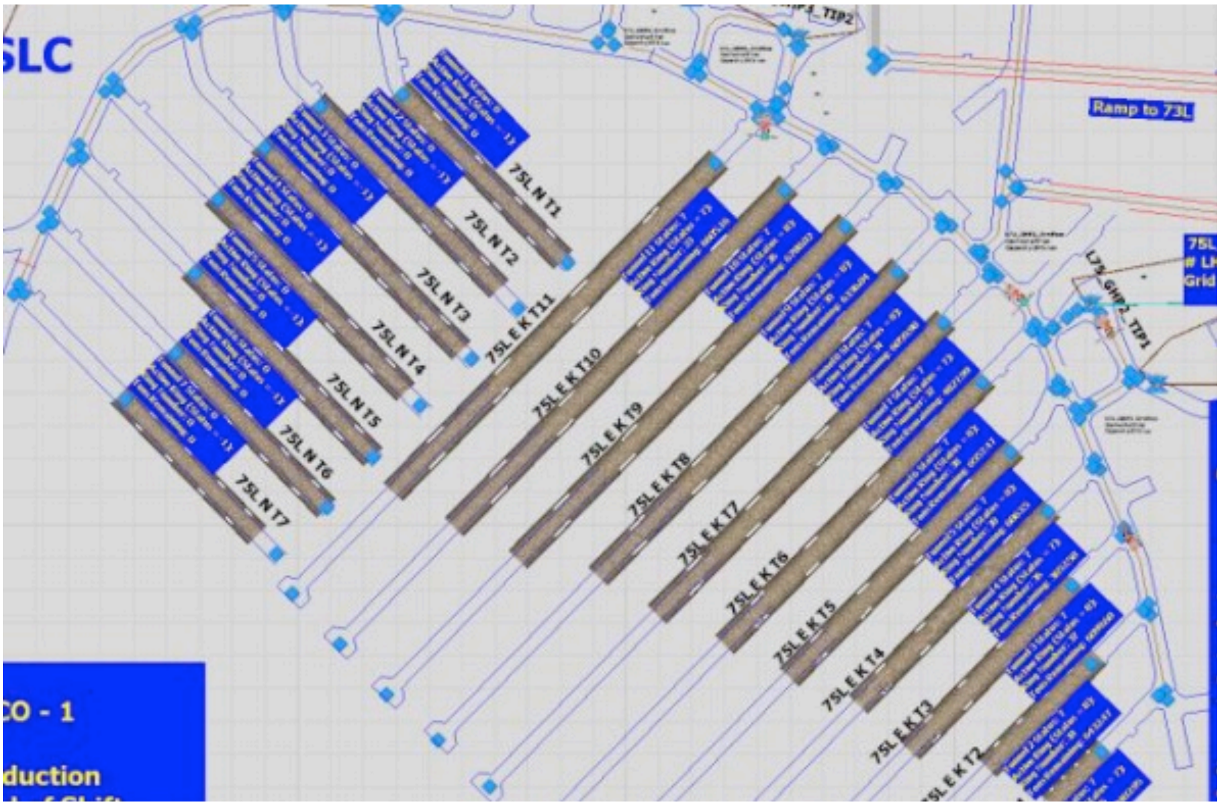

Figure 4. Illustration of the layout of 75 Level fitted with objects and the remaining rings to be extracted indicated as brown bars (Source: Oosthuizen, 2021).

Figure 5. Moveable objects indicating LHD in red, drill rig in yellow and charging rig in brown (Source: Oosthuizen, 2021).

The input parameter data was used to define object properties, while the output parameter data was compared to the historical production data. This ensured that the model reliably simulated the actual production system. To establish baseline values, data for four months was evaluated based on planned and actual production results as presented in Table II.

Table II. Actual versus planned monthly production tonnes between December 2019 and March 2020 (Source: Adapted from Oosthuizen, 2021)

Month	Actual tonnes	Planned tonnes	% Difference
December 2019	220,684	176,378	-20.07%
January 2020	265,196	223,053	-15.89%
February 2020	258,204	241,585	-6.43%
March 2020	202,450	270,017	+33.37%

Table II shows that February 2020 had planned tonnes that were relatively the closest to the actual tonnes achieved. Using this month's actual production results, a moving average of 245,929 tonnes was calculated after 15 Simio simulations. This is because the total moving average of simulated tonnes becomes relatively stable at about 245,929 tonnes after 15 simulation runs as shown in Figure 6. The input parameters and process logic of the model were evaluated using data collected from the mine's production system and performing 15 simulation runs at a time. The moving average of 245,929 tonnes was then used as the baseline tonnage to compare all the simulation results.

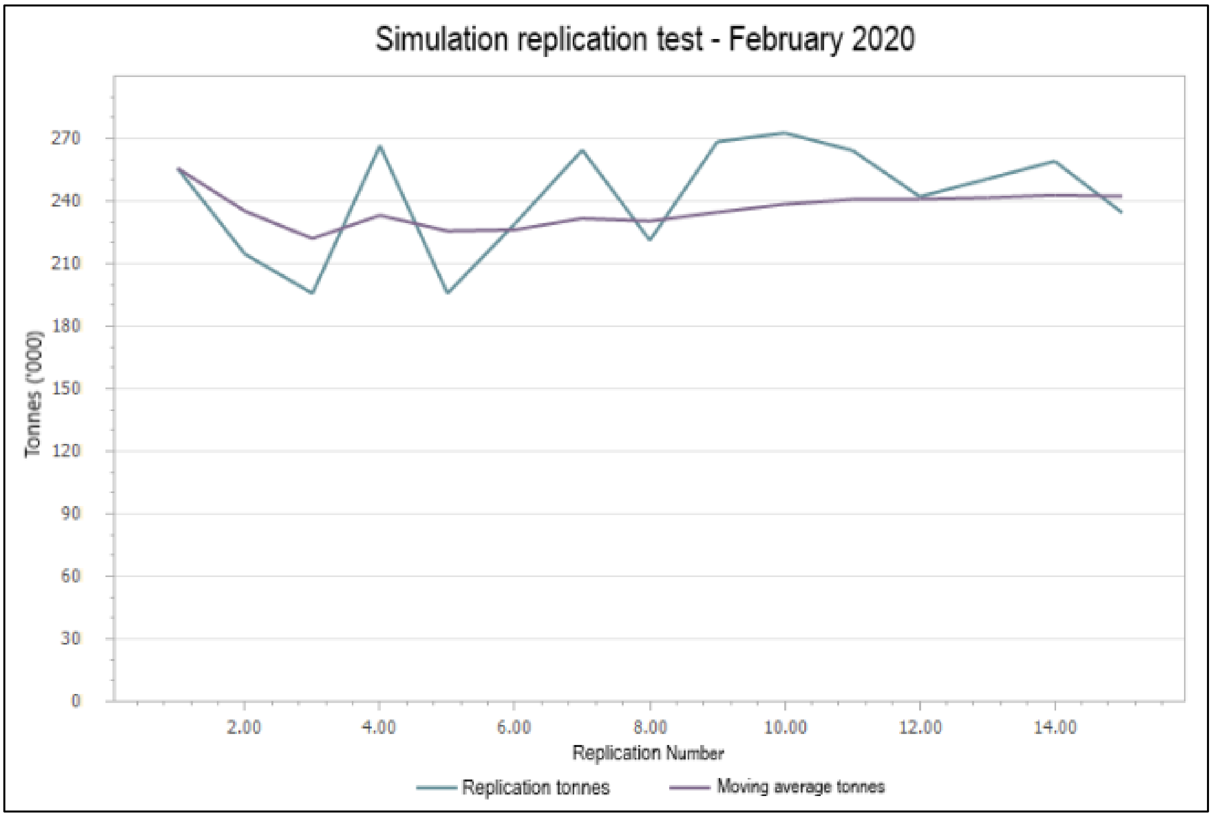

Figure 6. Moving average tonnes of simulation replication test run for February 2020 ((Source: Oosthuizen, 2021).

During the simulation runs, each input parameter for the production cycle activities was adjusted in increments of 10% below or above the baseline value, for example, -30% -20%, -10% or +10%, +20%, +30% as shown in Table III to establish a preliminary ranking of input parameters. Where an input parameter could not be adjusted by a percentage change as it could only be changed using integer increments, as in the case of vehicles or number of overtime weekends, such increases or decreases were applied, and normalised to a percentage increase. When a parameter for a production activity was changed, all other parameters were set to their respective baseline parameter values to allow estimation of sensitivity of the production system to the changes in the parameter and how it impacted the production throughput.

Table III. Preliminary ranking of input parameters as the most significant constraints on FDM's production system (Source: Oosthuizen, 2021)

Input Parameter	**Unit**	**Value**							
		Worsen			**Baseline**	**Improve**			
		30%	**20%**	**10%**		**10%**	**20%**	**30%**	**Percentage change in production output**
Scheduled production time	Hours	-28.73	-20.62	-14.27	0.00	4.94	19.34	34.46	
Load-haul-dump (LHD) units in use	Machines	-30.70	-21.26	-11.31	0.00	10.61	18.05	25.61	
Tunnels available for loading	Tunnels	-30.70	-21.26	-11.31	0.00	10.61	18.05	25.61	
LHD load size	Tonne	-29.51	-18.93	-10.55	0.00	7.72	11.97	28.32	
LHD tramming speed (full)	Km/h	-23.06	-11.04	-14.53	0.00	1.13	9.89	8.17	
LHD tramming speed (empty)	Km/h	-14.68	-9.39	-8.03	0.00	2.28	3.67	1.95	
Overtime weekends	Weekends	-7.86	-5.24	-2.62	0.00	1.16	2.33	3.49	
Drill rigs in use	Machines	-4.32	-2.88	-1.44	0.00	1.44	2.88	4.32	
Charging rig tramming speed	Km/h	-3.95	-5.21	-1.66	0.00	-4.62	0.21	-3.58	
Probability of grid being available	After # Tips	0.30	-5.35	-7.58	0.00	-0.21	2.63	-1.19	
Grid clean time	Minutes	-2.10	-4.17	-3.58	0.00	2.84	-2.02	-2.77	
Drill rig tramming speed	Km/h	0.92	0.30	-5.57	0.00	0.49	-6.52	-1.04	
Allowed LHD - 70 Level (2)	Machines	-2.79	-1.86	-0.93	0.00	0.54	1.07	1.61	
Allowed LHD - 73 Level (4)	Machines	0.35	-1.69	-0.84	0.00	-0.97	-1.95	-3.68	
Charging rig setup time	Minutes	-5.84	3.54	-2.78	0.00	-5.05	1.67	0.16	
Charging time per ring	Hours	-0.78	-2.47	0.69	0.00	2.77	-8.16	0.89	
Charging rigs in use	Machines	1.99	1.33	0.66	0.00	-0.55	-1.11	-1.00	
Allowed LHD - 78 Level (3)	Machines	2.85	1.90	0.95	0.00	0.00	0.00	0.00	
Allowed LHD - 75 Level (5)	Machines	-0.48	0.35	0.17	0.00	-0.21	-0.42	-0.64	
Drilling time (per ring)	Hours	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
LHD fuel capacity	Litres	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Fixed rock breaker availability	Percent	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

The final ranking of parameters (or constraints) was made after taking into consideration validation discussions with the mine planning team and cross-checking with historical data. The ranking of constraints using a combination of the simulation model, historical data analysis, and qualitative discussions added more depth and holistic evaluation to the ranking process. The final ranking of parameters (or constraints) on the FDM production system is illustrated in Table 4 for the top ten significant constraints. These constraints can be used to either increase the production throughput, decrease the effort required to achieve planned targets or reduce the production system's operational costs. Due to the intricate nature of interconnectedness of some of the constraints as seen in Table IV, several overarching approaches assist in concurrently addressing some of the constraints and details of these approaches are contained in Oosthuizen (2021).

Table IV. Final constraint ranking of FDM's production system (Source: Adapted from Oosthuizen, 2021)

Ranking	Constraint	Constraint description	Impact of constraint and associated factors
1	Scheduled production time	The hours available per day for production.	Scheduled production time per shift impacts ROM tonnage because an increase in production time will almost result in a similar increase in ROM tonnage, provided workers have high utilisation of the time.
2	LHDs in use	The average number of LHDs in use during production.	The number of LHDs proportionately impacts ROM tonnage since increasing the LHDs initially increases ROM tonnage. However, the relationship is not linear as the effect of adding more LHDs starts diminishing due to increased traffic congestion. For the FDM mining footprint, it is ideal to have nine LHDs always running and two on standby to immediately replace any LHD that breaks down.
3	Tunnels available for loading	The number of available tunnels from which ore is loaded.	The number of tunnels available for loading impacts ROM tonnage as increased tunnel availability will almost lead to an increase in ROM tonnage. At FDM available production tunnels varied from 31 to 34 due to several factors such as hang-ups in draw points, high waste ingress reported in draw points, tunnels being re-supported due to damage from blasting or loading, footwall requiring maintenance or fixing of ventilation infrastructure damaged during loading.
4	LHD load size	The payload in tonnes of each LHD bucket.	LHD load size proportionately affects ROM tonnage in general, where the Sandvik LH410s at FDM are fitted with a 10-tonne bucket capacity. Load size is affected by several factors such as, degree of fragmentation of blasted rock, density of material loaded (waste has a higher density than ore at FDM) and loading skills of an operator in achieving higher bucket fill factors.
5	LHD tramming speed	The average travelling speed of an LHD between the draw points and tips.	LHD tramming speed size proportionately affects ROM tonnage in general and is affected by various factors such as roadway conditions, traffic congestion in section due to other LHDs, trackless mobile machines or pedestrians and operator skill.
6	Production days scheduled	The number of days available in a month to run production.	The number of production days scheduled per month generally has a similar impact like scheduled production time per shift on ROM tonnage. At FDM, the planned production days per month were 20 but were sometimes increased to 26 by working overtime on weekends, although the overtime led to an increase in unit operating costs.
7	Drill rigs in use	The number of drill rigs needed to drill the planned production rings and re-drill damaged rings.	Intuitively, more drill rigs should lead to an increased inventory of pre-drilled rings and consequently increased ROM tonnage. However, this was difficult to simulate because at FDM inventories of four to six rings per tunnel are drilled in advance before the month in which it is blasted, causing a time lag. At FDM four drill rigs are required to drill per day in a planned 20-day production month. This number is affected by several factors such as scheduled production time, skill of a drill rig operators, breakdowns, setting-up time and connecting to the WiFi to receive drill plans, or relocating the rig to another tunnel or ring.
8	Drilling quality	The quality at which rings need to be drilled to facilitate ore flow between sub-levels and adjacent tunnels successfully.	Poor drilling accuracy leads to poor blasting resulting in, for example, corrective drilling being required causing more tunnels becoming unavailable, or poor fragmentation that causes delays on the tip.
9	Charging and blasting quality	The standard of charging and blasting practices that can successfully facilitate ore flow between sub-levels and adjacent tunnels, and to achieve optimal fragmentation.	Poor charging and blasting practices can result in planned ROM tonnages not being achieved, since such practices can lead to poor fragmentation that causes delays on the tip, compaction of material in the draw points, damage to the brow and support, or damage to pre-drilled rings that would require re-drilling leading to tunnel unavailability.
10	Tip availability	The availability of a tip when an LHD wants to tip or multiple LHDs want to tip consecutively.	Tip unavailability negatively impacts the achievement of planned ROM tonnage. Tips become unavailable for several reasons such as large rock fragments that cannot go through the tip grid, requiring rock breakers to crush them to size; rock breaker breakdowns, or presence of pieces of steel requiring time to clean the grid.

EXAMPLE MITIGATION MEASURES ON CONSTRAINT 'SCHEDULED PRODUCTION TIME'

Each of the ten top-ranked constraints was analysed in detail to propose possible mitigation measures and this was done in consultation with the FDM mine planning team to ensure pragmatism of the mitigation measures. For example, with the 'scheduled production time' constraint, it was observed that at the time of the study, the mine was operating a three-shift configuration consisting of nine-hour shifts that resulted in approximately 16.5 production hours per day (Oosthuizen, 2021). Lost time was mainly due to shift changeovers as there were inherent pre- and post-shift delays and intra-shift delays. Personnel were limited to travel via the shaft conveyance system to underground workings in the shaft conveyance system which was limited to carrying 100 people at a time (Oosthuizen, 2021). In addition, workers had to travel from the shaft to the designated waiting places where the start-of-shift meetings are conducted before they could travel to their respective workplaces. Intra-shift delays were due to inevitable safety checks and relief breaks taken by the workers.

There are many available ways for increasing the production time which include reducing the length of pre- and/or post-shift delays or cutting out a shift changeover by adopting a two-shift configuration consisting of 12-hour shifts, instead a three-shift configuration with nine-hour shifts. With this change in shift configuration, it was estimated that about two hours could be gained for production time per day, and this could translate into about an additional 20,000 tonnes a month in production throughput. However, caution should be exercised with this approach as it could potentially lead to increased personnel fatigue beyond nine hours and workers becoming less efficient in the last three additional hours in a shift. To overcome this challenge, it was proposed that the two-shift configuration should comprise of two 12-hour shifts in a compressed four-day cycle rotation (as per the labour law) so that at the end of the fourth day for each crew, a new cycle starts for another crew. In this way it is possible to then increase the total available production time during a month by having less shift changeover delays and more production days.

CONCLUSIONS

This paper has demonstrated that a mining production system is inherently limited from reaching its planned production throughput by system constraints. Approaches to resolving system constraints generate solutions that do not enable the system to reach its throughput capacity unless they are holistic in nature to enable continuous improvement. In the case of FDM, two successive studies indicated this shortcoming and prompted the study presented in this paper to be undertaken. The approach utilised in this paper was a combination of a system modelling approach and the TOC methodology. The combined approach identified and finally ranked ten constraints which were validated by the FDM mine planning team and how they could be mitigated to improve system throughput. An example of how the 'scheduled production time' constraint from among the ten top ranked constraints could be resolved, was through changing the shift configuration. Details of other initiatives planned to further improve performance by resolving the other nine constraints are explained in Oosthuizen (2021) and these serve as a foundation for business improvement. The combined approach was viewed by the FDM mine planning team as a more comprehensive approach that should be undertaken as a precursor activity in identifying and ranking system constraints to inform future production system improvement studies and plans.

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Bw, an accomplished professional in the field of underground mining, currently serves as a Specialist Mining Engineer at AngloGold Ashanti's Geita Gold Mine in Tanzania. With expertise in underground mining, Bw plays a crucial role in providing leadership and support for mine planning across three underground operations, encompassing both short-term and long-term planning horizons. Prior to this, Bw held a group position of overseeing long-term strategic mine planning for Petra Diamond's Finsch Diamond Mine.

Possessing a Master's degree in Mining Engineering from Wits University, Bw brings extensive knowledge and experience in various aspects of mining, including mine design, scheduling, and optimization. Bw's strengths lie in solving complex problems, employing critical thinking skills, and effectively managing projects associated with massive underground mining operations.