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Application of the theory of constraints to the pillar development cycle of an underground coal mine

Ernest Baafi
University of Wollongong, ebaafi@uow.edu.au

Dalin Cai
University of Wollongong, dalin@uow.edu.au

Ian Porter
University of Wollongong, iporter@uow.edu.au

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Abstract
The underground coal mine pillar development cycle consists primarily of three sets of interdependent and synchronised cycles, i.e., the coal cutting cycle by a continuous miner (CM), the support cycle by a roof bolter and the coal transport cycle to the boot end by a shuttle car. Coal cutting by a CM is generally not seen as a constraint as, in almost all cases, the capacity of the CM far exceeds the demand placed on it. Therefore, in essence, the pillar development process can be either transport constrained or support constrained. Using a discrete simulation model, it was shown that for a case study mine a CM configured with two bolting rigs was support constrained when the distance from the boot end to the face was short. It was suspected that as the distance from the face to the boot end increased and development would change from being support constrained to transport constrained. For this case however, introduction of additional bolting rigs did not change the development rate significantly with an increasing distance from the face to the boot end, thus confirming the initial configuration of the mine was entirely support constrained. Simulation of a bolter-miner configuration with six bolting rigs and concurrent bolting indicated that such a system is a transport constrained. With the introduction of a continuous haulage system (CHS), a bolter-miner configuration with six bolting rigs and concurrent bolting, changed the system to support constrained. This maybe explained by the fact that a CHS has a much higher transport capacity than a shuttle car. The simulation results showed an approximate 25% reduction in hours to develop five pillars using a CHS instead of two shuttle cars. The paper discusses additional simulated results of a series of two-heading roadway development scenarios to demonstrate the Theory of Constraints implementation methodology.

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Application of theory of constraints methodology to the pillar development cycle of an underground coal mine

Dalín Cai, Ernest Baafi* & Ian Porter

School of Civil, Mining and Environmental Engineering/University of Wollongong, Associate Professor, +61242213031, ebaafi@uow.edu.au

School of Civil, Mining and Environmental Engineering, University of Wollongong, Associate Professor, +61242213451, iporter@uow.edu.au

School of Civil, Mining and Environmental Engineering, University of Wollongong, PhD Student, dc840@uow.edu.au

ABSTRACT

The underground coal mine pillar development cycle primarily consists of three sets of interdependent and synchronised cycles, i.e. the coal cutting cycle by a continuous miner (CM), the support cycle by a roof bolter and the cut coal transport cycle to the boot end by a shuttle car. Coal cutting by a CM is generally not seen as a constraint as in almost all cases, the capacity of the CM far exceeds the demand placed on it. Therefore, in essence the pillar development process can be either transport constrained or support constrained.

Using a discrete simulation model, it was shown that for a case study mine a CM configured with two bolting rigs was support constrained when the distance from the boot end to the face was short. It was suspected that as the distance from the face to the boot end increased the development would change from being support constrained to transport constrained. For this case however, introduction of additional bolting rigs did not change the development rate significantly with an increasing distance from the face to the boot end, thus confirming the initial configuration of the mine was entirely support constrained.

Simulation of a bolter–miner configuration with six bolting rigs and concurrent bolting indicated that such a system is transport constrained.

With the introduction of a continuous haulage system (CHS), a bolter–miner configuration with six bolting rigs, concurrent bolting, changed the system to support constrained. This may be explained by the fact that a CHS has a much higher transport capacity than a shuttle car. The simulation results showed an approximate 25% reduction in hours to develop five pillars using a CHS instead of two shuttle cars.

The paper discusses additional simulated results of a series of two-heading roadway development scenarios to demonstrate Theory of Constraints implementation methodology.
INTRODUCTION

Various innovative technologies and systems such as bolter miners, self-drilling bolts, continuous haulage systems and monorail mounted services have been introduced in underground coal mines to improve the rate of roadway development. However, the inherently complex nature of interactions within the roadway development system gives rise to some very difficult challenges. The Australian coal mining industry needs a systematic methodology not only to facilitate the understanding of the complex roadway development systems and also to ensure that the limited capital available is spent on the appropriate roadway development equipment. The Theory of Constraints (TOC) is one such framework that can be used as a guide to facilitate the understanding of such a complex system interactions. TOC is a proven technique for evaluation of the performance of underground coal mines roadway development operations. In a roadway development environment, there exist a number of cyclic processes and a range of equipment. In a given scenario, any of these processes or equipment can be a potential constraint, i.e. the slowest processes or equipment in the system.

TOC IMPLEMENTATION METHODOLOGY

Implementation of Theory of Constraints (TOC) involves the following steps (Goldratt, 1999):

Step 1: Identify the system's constraint(s)
Step 2: Define the changes required and decide how to exploit the constraint(s)
Step 3: Elevate the system constraint(s)
Step 4: Reassess the system performance
Step 5: Close the loop if the constraint has been broken

Figure 1 illustrates this TOC implementation process for underground coal mine roadway development process. Once a productivity improvement measure has been implemented, the system performance must be re-assessed to identify changes in the nature of constraint and the whole cycle must be repeated again as shown in Figure 1. The first step in TOC implementation is to identify the correct areas for improvement. Broadly, underground coal mine roadway development processes can be categorised into two distinct process sets (Figure 2):

- **Cyclic Processes**: These are the processes which are interdependent e.g. the cutting/bolting/transport cycle and the panel advance cycle. TOC can be individually applied to these and improvement in efficiency of either of these process sets will improve the efficiency of the system as a whole.

- **Parallel Processes**: These processes would ideally be performed in parallel to other tasks and so would not affect the efficiency of other operations. But if not carried out in parallel they may constrain the capacity of existing bottlenecks.
Determine Process rate (meters advanced/operating hour) with increasing distance from the boot end (B.E.) over a pillar development cycle

Plot a graph with B.E. distance on the x-axis and the process rate (m/hr.) on the y-axis

Observe the shape of the resulting graph

The process is transport constrained

The process is support constrained

Use cycle time and capacity analysis to determine the true constraint in the transport cycle

Identify the applicable solutions to elevate the constraint

Plot the bubble graph using:
- Cost of implementation as x-axis
- Ease of implementation as y-axis
- Diameter of bubble - % improvement in panel cycle time

Select the most suitable alternative(s). Ideal alternative:
- Low Cost of implementation
- High Ease of implementation
- Large bubble diameter

Implement the selected alternative(s) and reassess the system performance

Figure 1: Proposed TOC Implementation Methodology
Since the scope of this paper is limited to the pillar development cycle, the optimisation of panel advance system will not be considered here. However, it must be noted that the proposed TOC methodology for the pillar development cycle can easily be repurposed for application to the panel advance cycle.

As depicted in Figure 2 above, the pillar development cycle primarily consists of three sets of interdependent and synchronised cycles i.e. cutting cycle, support cycle and transport cycle. As far as the parallel processes are concerned, they do not act as constraints themselves, but if not performed in parallel, they may constrain the capacity of existing bottlenecks further. Also, cutting is generally not seen as a constraint as in almost all cases, the capacity of the continuous miner far exceeds the demand placed on it. Therefore, in essence the development process can be either transport constrained or support constrained. This concept simplifies the entire process of TOC implementation as now the focus can be narrowed down to only two system constraints out of many potential ones.

One of the most suitable techniques for determining whether the process is support or transport constrained is to plot process rates (meters advanced/operating hour) against the increasing distance.
(meters) from the boot end (Porteous, 2008). Based on the slope of the resulting graph, conclusions about the nature of the constraint can be made. For example, consider the following graph in Figure 3.

![Graph showing process rate variations in case of a support constrained process](image)

**Figure 3: Process rate variations in case of a support constrained process**

As is evident from the above graph, the process rate in this scenario remains more or less constant irrespective of the distance from the bootend. As the distance from the bootend increases, the demand placed on the transport system increases as well. Now, if the capacity of transport system is equal to or greater than the demand placed on it, the process rate will tend to remain constant despite the increasing distance from the bootend. In such a case, it will be reasonable to deduce that the system is support constrained.

Now, consider another scenario illustrated by the graph in Figure 4:

![Graph showing process rate variations in case of a transport constrained process](image)

**Figure 4: Process rate variations in case of a transport constrained process**

In this case, the process rate tends to drop as we move away from the bootend. Therefore, it will be reasonable to deduce that the system is transport constrained because in this case the capacity of the transport system is less than the demand placed on it.

In general, if the process rate drops considerably with increasing distance from the bootend, then the system is likely to be transport constrained. However, if the process rate remains constant then the system is most likely to be support constrained (Porteous, 2008). However, one may encounter much more complex scenarios than the one described above, where the process rate may remain constant for a considerable distance and then start dropping. In such ambiguous cases, a delay state analysis can be
used in combination with the above methodology to identify the nature of constraint. In the subsequent sections, a FlexSim based simulation model has been used to demonstrate how process rate analysis can be combined with the delay state analysis for this purpose.

The above methodology helps in ascertaining whether the system is transport constrained or support constrained. Once the basic nature of constraint has been identified, it is necessary to identify the particular process or equipment within the system which is the true constraint e.g. if the system is transport constrained, the constraint could be the shuttle car or the feeder/breaker or even the panel conveyor. For this purpose, it might be necessary to determine the equipment capacities to identify the true constraint. A conventional cycle time analysis can be used for this purpose. Time measurements can be taken on all the processes in the section and they can be analysed to determine the capacity of each equipment.

**TOC IMPLEMENTATION USING A SIMULATION MODEL**

TOC is a management framework that can be used for improving system performance but it does not provide any detailed analytical tools for analysing system performance. This gap can be filled by computer simulation.

**SIMULATION MODEL OVERVIEW**

A discrete simulation model developed by Cai et al (2012) has been used to demonstrate the proposed TOC implementation methodology. This model based on FlexSim 3D virtual reality environment was used to identify the system constraints, to evaluate the effectiveness of available alternatives and also to predict the shift of the constraint.

Being based on FlexSim, the simulation model developed by Cai et al, (2012) is capable of simulating the complex set of interdependencies between various roadway development processes and was considered suitable for the requirements of this study.

The simulation model has the ability to:

- Reproduce the randomness associated with delays that occur during the process of roadway development. The main mining processes and associated delays which the model is perfectly capable of simulating are:
  a. the Continuous Miner cutting coal from the coal seam and loading it onto the shuttle car or a continuous haulage system;
  b. Coal tramming by the shuttle car to the bootend
  c. Roof/rib support operations
  d. Panel movement operations
  e. Parallel processes (vent tube extension, stone dusting etc.)
  f. Breakdown time and other delays

- Simulate what-if scenarios as a means for assessing the effectiveness of alternatives and
also for predicting the shift of the constraint.

SIMULATION MODEL CONFIGURATION AND OUTPUT

Using the FlexSim model described above, a series of two-heading roadway development scenarios were simulated to demonstrate the proposed TOC implementation methodology:

- Scenario 1: Miner – Bolter Continuous Miner (CM) configuration with only two bolting rigs
- Scenario 2: Miner – Bolter CM configuration with six bolting rigs and non-concurrent bolting
- Scenario 3: Bolter - Miner CM configuration with six bolting rigs and non-concurrent bolting
- Scenario 4: Bolter - Miner CM configuration with six bolting rigs and non-concurrent bolting along with self-drilling bolts (SDBs)
- Scenario 5: Bolter - Miner CM configuration with six bolting rigs, non-concurrent bolting and 2 shuttle cars (SCs)
- Scenario 6: Bolter - Miner CM configuration with six bolting rigs, non-concurrent bolting and 2 shuttle cars (SCs) along with self-drilling bolts (SDBs)
- Scenario 7: Bolter - Miner CM configuration with six bolting rigs, non-concurrent bolting and a Continuous Haulage System (CHS)
- Scenario 8: Bolter - Miner CM configuration with six bolting rigs, non-concurrent bolting with a Continuous Haulage System (CHS) and SDBs
- Scenario 9: Bolter - Miner CM configuration with six bolting rigs, concurrent bolting with a Continuous Haulage System (CHS) and SDBs

The main model configuration parameters used for the various scenarios are listed below:

- Roadway Dimensions: Width=5 m Height=3 m
- Pillar Dimensions: Length=110 m Width=40 m
- Bootend to Cut through distance=20 m

Figure 7: Two-heading roadway development configuration (Cai et al, 2012)
- Length of gas drainage stub = 5 m
- Overdrive distance = 20 m
- Support Density: 6 roof bolts and 4 rib bolts per m advance

It must be noted here that the simulation model used takes into account a number of other fixed and random activities, whose parameter values have not been listed above. For the purposes of this study it was considered suitable to select default values for such model parameters.

Figures 8-25 illustrate the results obtained from the simulation of the above scenarios. The graphs included in this section indicate the process rate variations over a single pillar development cycle and so do not include the panel advance delay.

In the first scenario, a miner-bolter CM configuration with two bolting rigs and one shuttle car was simulated. The results of the simulation are as shown in Figure 8. From the slope of the graph it is clear that the process rate does not vary much with increasing distance from the boot end indicating that the process is support constrained.

![Figure 8: Simulation results for scenario 1](image)

It must be noted that the above scenario was simulated without taking the face operation delays into account which include delays due to activities like ventilation tube extension, stone dusting and supplying the continuous miner. Figure 9 illustrates the process rate graph when such delays are taken into account. It is clear from this graph that these ancillary operations or the parallel processes tend to affect the process rate negatively. However, a linear trend line plotted through the graph indicates that the process rates do not vary much with increasing distance from the bootend. This reaffirms the argument presented before that parallel activities do not act as constraints themselves but they constrain the capacity of existing bottlenecks. The roadway development system for scenario 1 is still support constrained.

For subsequent scenarios, the results are presented without taking these face operation delays into account. This is to ensure clarity of illustration. However, it must be noted that in practical scenarios such delays would have a considerable impact and as a consequence the actual process rate may be quite different from the simulation results shown below.
The introduction of additional bolting rigs in scenario 2 was expected to result in an improvement in process rate as compared to the original scenario. The results of the simulation are as illustrated below. It is quite clear from the graph below that introduction of additional bolting rigs has improved the process rates. The system is in a transition state and is moving towards being transport constrained. However, the variation in process rates with distance from the bootend is only minor and a quick glance at the delay state chart (Figure 11) suggests that support activities are still the biggest source of delay, indicating that the process is still support constrained.

In a number of practical scenarios, the process rate analysis might not be conclusive enough to determine the nature of constraint e.g. in case of scenario 2, the process rates vary to a limited extent and it is difficult to ascertain whether the process is in a transition state or it has become transport constrained. In such complex scenarios, the process rate analysis can be combined with a delay state analysis to yield conclusive results. The delay charts included in this section depict the delay state of the system over a 5 pillar development cycle and have been auto-generated using the FlexSim simulation model under consideration.
The following graph illustrates the results from the simulation of scenario 3. The slope of the graph suggests a shift in the nature of constraint compared to scenario 2. A bolter-miner allows the cutting and bolting operations to be performed in parallel resulting in a considerable improvement in performance and a shift in the nature of constraint. The delay state chart (Figure 13) confirms this shift as transport system is now the biggest source of delay. Clearly, the system is now transport constrained.
The purpose of simulating scenario 4 was to prove the fundamental premise of Theory of Constraints that improvement in productivity of non-bottleneck processes would not lead to an improvement in system performance. As discussed before, the roadway development configuration represented by scenario 3 is transport constrained, so an improvement in support mechanisms should not lead to an improvement in system performance. In scenario 4, self-drilling bolts in place of conventional bolts were employed keeping all other parameters the same as scenario 3. The results from the simulation are depicted below. From the graph it is evident that the overall process rate remains unchanged. The delay state chart shown in figure 15 confirms this view indicating that the process is transport constrained. The time taken to develop 5 pillars as determined from the simulation model was 461 operating hours which is exactly the same as in the case of scenario 3.

In scenario 5, a second shuttle car was
introduced keeping all the other parameters same as scenario 3. An improvement in capability of the transport system further improved the process rate as illustrated in Figure 16.

Figure 15: Delay state analysis for scenario 4

It must be noted here that though the productivity of the system has improved the nature of constraint has still not changed. This scenario is another good example of complex cases where a combination of process rate analysis and delay state assessment is required to ascertain the true nature of the constraint. In this case, by using the process rate analysis alone, it may be difficult to determine the nature of constraint but the delay state chart shows that ‘waiting for transporter’ is still the biggest source of delay indicating that the process is still transport constrained.

Figure 16: Simulation results for scenario 5
In scenario 6, self-drilling bolts were employed, keeping all other parameters the same as scenario 5. It is evident from the graph below that though the process rates are higher at the start of the cycle, the overall process rate remains unchanged compared to scenario 5. This is because the system is transport constrained and therefore an improvement in support capability will not improve system productivity. The time taken to develop 5 pillars as determined from the simulation model was 405 operating hours which is a marginal improvement over scenario 5 (410 operating hours) but not substantial enough to justify an investment in self-drilling bolts.

The introduction of a Continuous Haulage System (CHS) in scenario 7, however, produces some considerable results. The system process rate has improved considerably as depicted in the Figure 20 and the system is now support constrained. This is expected as a CHS has much higher transport capacity compared to a shuttle car. The time taken to develop 5 pillars as determined from the simulation model was 366 operating hours which is a considerable improvement over scenario 6.
Figure 19: Delay state analysis for scenario 6

Simulation results for scenario 7
Figure 21: Delay state analysis for scenario 7

The introduction of self-drilling bolts in place of conventional bolts in scenario 8 and introduction of two additional CM mounted bolting rigs in scenario 9 further improves the process rates as depicted in the figures 22-25 below.

Figure 22: Simulation results for scenario 8
Application of Theory of Constraints is a Process of On-going Improvement (POOGI). As illustrated above, once a productivity improvement measure has been implemented, the system performance must be re-assessed to identify changes in the nature of the constraint and the whole cycle of improvement must be repeated again. In this study, a number of scenarios have been simulated to demonstrate how a combination of delay state and process rate analysis can be used to continually improve the efficiency of pillar development cycle. The time taken to develop 5 pillars was observed to improve from 568 operating hours in case of scenario 1 to 253 operating hours in case of scenario 9. However, the process of on-going improvement does not stop here. From the delay state chart of scenario 9, it is evident that the major delay is now contributed by the panel advance processes. Therefore, the focus at this point must change to TOC optimisation of the panel advance cycle.

As explained before, panel advance is a cyclic process set in itself and therefore, TOC can be independently applied to it. Since the scope of this paper is limited to the pillar development cycle, the TOC optimisation of panel advance cycle has not been explained but it must be noted that the TOC implementation methodology described above can easily be repurposed for application to the panel advance cycle as well.

CONCLUSIONS

As discussed before, Theory of Constraints is a management framework that can be used for improving system performance but it does not provide any detailed analytical tools for analysing system performance. This gap needs to be filled by computer simulation. The basic objective of simulating the above development scenarios was to demonstrate how TOC can be combined with simulation to yield practical improvement suggestions.
Two most critical steps in the TOC implementation process are concerned with the identification of constraint and the computation of ‘Magnitude of Expected Improvement’ that can be brought about by implementing a particular improvement measure. From the above analysis, it is clear that a discrete simulation model like the one described above can help practitioners highlight process constraints and determine how much improvement can be achieved by changing various operational parameters before costly field tests are undertaken.

It is important to realise here that the simulation results provided in the preceding section are for illustrative purposes only. The purpose of this exercise was to demonstrate that simulation models can greatly simplify the process of TOC implementation by helping practitioners to identify the system constraints, to evaluate the effectiveness of available alternatives and also to predict the shift of the constraint. However, in practice the results obtained may be quite different from those predicted by the simulation model.

Through this paper every effort has been made to demonstrate that principles of TOC management can be systematically applied to distinct process sets within underground coal mining. It is expected that this paper would serve as an effective introduction to TOC implementation for mining personnel with limited to no knowledge of this paradigm.

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*Corresponding author: School of Civil, Mining and Environmental Engineering/University of Wollongong, Associate Professor, Faculty of Engineering & Information Sciences, University of Wollongong, Wollongong, Australia. Phone: +61 242213031. Email: ebaafi@uow.edu.au