Using FlexSim to Simulate the Logistics Relationship between MaterialsSupplying and Roadway Development

Liyong Cai
University of Wollongong

UNIVERSITY OF WOLLONGONG
COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author.

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Using FlexSim to Simulate the Logistics Relationship between Materials Supplying and Roadway Development

Liyong CAI

"This thesis is presented as part of the requirements for the award of the Degree of the Master of Philosophy

University of Wollongong"

8.2017
ABSTRACT

Underground coal mine logistical operations involve activities such as transportation of coal from the longwall faces and roadway development units to the mine surface, transportation of consumable materials, operational crews, mining equipment and other supplies from the mine surface to numerous underground drop points to support the four key operations of the mine: longwall production, roadway development, gas drainage and mine construction. Underground coal mining logistics can be clustered into the three broad groups of activities: transportation/delivery of coal from longwall extraction face, through the belt conveyor system, to the mine surface; transportation of materials and other supplies (e.g. consumables) from the mine surface to the underground buffer areas and then to the final consumption points using multiple means of transport (underground development headings being mostly, for the purpose of roof support and ancillary advance); and transportation of personnel to different working sites underground, mainly using shafts and drifts.

This thesis studied underground coal mining logistics using a modern simulation program by integrating the underground mining operations into one simulation model and focusing on the roadway development unit only. The model has been validated with historical performance data and input parameters collected from mine sites. By considering the randomness and real interactions between every operation, the
simulation results demonstrated that it’s a very viable method of analysing system constraints and optimizing the performance of underground coal mining logistics systems. It allows engineers, mine operators and researchers to optimize the selection of equipment and other resources through the way of evaluating alternative “what if” scenarios via the model, rather than relying on costly field trials. The case studies fully examined the logistics of both coal transportation from the continuous miner to the conveyor belt and the material supply from the pit bottom to the development headings.

The roadway development rate is affected by multiple factors. The simulation and analysis of coal transportation together with support operations showed a potential of 30% performance increase with current support technology and faster coal transportation. The historical support operation was about 17 minutes per metre. If the support operation can be improved to be within 12 minutes per metre which is observed from practice, the overall performance would be improved by 20%, from about 20m a day to 24m a day. If the 12 minutes per metre support operation could be achieved, the performance can be further improved by another 10%, from about 24m a day to more than 26m a day by utilizing a faster Shuttle Car for the coal transport to the boot end.

As for the supply of material to the development face, the rate of material supply has a minor effect on the roadway development rate. With regard to the duration and frequency of the material supply operation and the distance from the material storage to
the surface, the duration of material supply has a linear relationship with the roadway development rate across all reasonable supply intervals. However, with four times the duration change, the development rate only changes from about 3.33% at the least frequent supply to about 8.33% at the most frequent supply, which means the material supply duration only has a minor influence on the roadway development rate. Further simulation studies demonstrated the material storage distance has basically a linear relationship with the roadway development rate. However, the effect is minor, where the change is only 0.7m per day (1%) with about a 500-metre difference overall with respect to the total distance. For every 100m decrease between the material storage and the development heading, there is an improvement of about 0.2% in the development rate.

Further, the simulation results and analysis support the opinion that the random long-time delay of logistical supply causes a major logistical issue which may come from the communication and scheduling of the material supply from outside the mine to the panel material storage area or the breakdown of machines. An average of two hours delay for every 40m advancement can cut down the total development rate by 15%, while a 22% development rate drop would be caused by an average of two hours delay at the frequency of about every 12 hours on average. The effect of both type of delays caused about a 39% drop in the development rate. With a one-hour incremental delay
applied to both types of delay simulated, there is a 51% decrease of the development rate. Respectively, an average of three hours delay for every 40m of advancement can cut down the total development rate by 20%, while a decrease of 33% in the development rate would come about by an average of three hours delay at the frequency of about every 12 hours on average.
ACKNOWLEDGEMENT

I would like to express my deep sense of thanks and gratitude to my supervisor, A/Professor Ernest Baafi and my co-supervisor, Dr. Senevi Kiridena for their guidance, advices, patience, encouragement and all other supports. Without these I would say I could not have finished this thesis.

Also, I want to show my gratitude to the late Mr Gary Gibson, A/Professor Ren Ting for their valuable information on underground coal mine practice and underground mine logistics, to both Mr Kevin Marston and Dr Dalin Cai for their help in reviewing this thesis. Special thanks to Dr Dalin Cai for his help in FlexSim modeling.

Finally, I want to express my gratitude to my parents for their love, support and encouragement; thanks for giving me the motivation to move forwards.
# TABLE OF CONTENTS

ABSTRACT .......................................................................................................................... i

ACKNOWLEDGEMENT ..................................................................................................... v

TABLE OF CONTENTS ..................................................................................................... vi

LIST OF FIGURES ............................................................................................................ x

LIST OF ABBREVIATIONS ............................................................................................... xv

1. GENERAL INTRODUCTION ......................................................................................... 1

   1.1. Introduction .......................................................................................................... 1

       1.1.1. Roadway development ............................................................................... 2

       1.1.2. Longwall production .................................................................................. 6

       1.1.3. Gas drainage .............................................................................................. 9

       1.1.4. Longwall changeover ............................................................................... 10

   1.2. Research Problem .............................................................................................. 13

   1.3. Aim and Objective of the Thesis ......................................................................... 16

2. ROADWAY DEVELOPMENT AND THE LOGISTICS ......................................... 18

   2.1. General ............................................................................................................. 18
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1.</td>
<td>Development methods</td>
<td>18</td>
</tr>
<tr>
<td>2.1.2.</td>
<td>Development sequences</td>
<td>19</td>
</tr>
<tr>
<td>2.1.3.</td>
<td>Roadway support</td>
<td>20</td>
</tr>
<tr>
<td>2.2.</td>
<td>Logistics in Underground Coal Mines</td>
<td>23</td>
</tr>
<tr>
<td>2.2.1.</td>
<td>Sub-Logistics system of coal transportation</td>
<td>27</td>
</tr>
<tr>
<td>2.2.2.</td>
<td>Sub-logistics system of material and personnel transport</td>
<td>31</td>
</tr>
<tr>
<td>2.2.3.</td>
<td>The “customer” in mine logistics systems</td>
<td>37</td>
</tr>
<tr>
<td>3.</td>
<td>MODELLING LONGWALL MINING LOGISTICS</td>
<td>40</td>
</tr>
<tr>
<td>3.1.</td>
<td>Operation Research Based Studies of Underground Mining Logistics</td>
<td>42</td>
</tr>
<tr>
<td>3.2.</td>
<td>Simulation Based Studies of Underground Mining Logistics</td>
<td>48</td>
</tr>
<tr>
<td>3.3.</td>
<td>Synthesis of Underground Mining Logistics</td>
<td>51</td>
</tr>
<tr>
<td>4.</td>
<td>DEVELOPMENT OF THE DISCRETE EVENT SIMULATION MODEL</td>
<td>53</td>
</tr>
<tr>
<td>4.1.</td>
<td>The Roadway Development Module</td>
<td>53</td>
</tr>
<tr>
<td>4.1.1.</td>
<td>The updates of the roadway development module in this project</td>
<td>60</td>
</tr>
<tr>
<td>4.1.2.</td>
<td>The redesign of the roadway object</td>
<td>64</td>
</tr>
<tr>
<td>4.1.3.</td>
<td>The updates of other objects of the roadway development module</td>
<td>68</td>
</tr>
<tr>
<td>4.2.</td>
<td>The Conveyor Module</td>
<td>69</td>
</tr>
</tbody>
</table>
4.3. The Transport Module ................................................................. 71

5. EXPERIMENT AND ANALYSIS ..................................................... 78

5.1. Basic Model Input Parameters .................................................... 79

5.2. The Shift Schedule and Delays .................................................. 81

5.2.1. CM007 Operation Data .......................................................... 81

5.2.2. CM008 Operation Data .......................................................... 84

5.3. The Simulation Results ............................................................ 87

5.3.1. Model validation ................................................................. 87

5.3.2. The coal transportation ........................................................ 89

5.3.3. The supply of support materials ............................................. 91

5.3.4. The effect of downtime and scheduling delay of material supply on the development ................................................................. 96

5.4. Summary on the simulation experiments ..................................... 98

6. SUMMARY AND CONCLUSION ................................................... 99

7. MODEL LIMITATION AND FUTURE WORK ................................ 101

8. REFERENCES .................................................................................. 103

9. APPENDICES .................................................................................. 113
9.1. APPENDICE A - the program script of the new designed roadway object... 113

9.2. APPENDICE B - Modules or variables that affect the development............ 126
LIST OF FIGURES

Figure 1.1 Four mine operations in underground longwall mining (Gibson, 2016)........2

Figure 1.2 A simplified underground coal mine system........................................3

Figure 1.3 The sequences of heading development..............................................5

Figure 1.4 Typical plan view of a series of longwall panels (MSEC, 2007)...............6

Figure 1.5 Longwall face equipment diagram (Hem, 2015).................................8

Figure 1.6 Surface and underground gas drainage examples (Sharma, 2008)........10

Figure 1.7 Longwall change-out critical path (Longwall Mining, 2017).................11

Figure 2.1 Cutting sequences of a two-heading roadway development (Birchall, 2007)
.................................................................................................................................19

Figure 2.2 Roof support operation on a Bolter Miner ..........................................21

Figure 2.3 Roadway roof and rib support plan (Birchall, 2007)............................22

Figure 2.4 Transportation of coal by belt conveyor ..............................................25

Figure 2.5 Underground mining logistics supplying system..............................25

Figure 2.6 The main components of logistics within a mine (Kiridena, 2017).........26

Figure 2.7 Integrated underground logistics system (Miwa and Takakuwa, 2011)......27

Figure 2.8 Armed Faced Conveyor (AFC) (Underground coal, 2017a)..................28
Figure 2.9 Possible options for coal haulage from roadway production face...........29

Figure 2.10 Joy UFB-22 Feeder-Breaker (Komastu, 2017)........................................31

Figure 2.11 Multi-Purpose Vehicle (MPV).................................................................33

Figure 2.12 Materials handling pods for different materials (Macquarie Manufacturing, 2017) .........................................................................................................................34

Figure 2.13 Dolly Car fitted for man riding and connecting to materials transport cars (-Underground Coal, 2017b) ..............................................................................................................35

Figure 2.14 Load Haul and Dump Quick Detachable System (LHD-QDS) (Impact Mining, 2017)..........................................................................................................................36

Figure 2.15 Specially designed vehicles for personnel transport (Basemesh, 2017) ....37

Figure 2.16 Continuous Miner....................................................................................38

Figure 2.17 MB450 Bolter Miner by Sandvik ...........................................................39

Figure 3.1 The queuing system of LHDs, production blocks and repair shop ..........43

Figure 3.2 Transport planning, steering and material tracking & tracing ..............46

Figure 3.3 Coal mine production logistics system structure (Feng et al., 2010)........49

Figure 4.1 The overview of the roadway development model MINESIM by Cai (2015) ........................................................................................................................................54
Figure 4.2 The capacity of the roadway development module (Cai, 2015).................56

Figure 4.3 Overview of the model in FlexSim working mode ..................................58

Figure 4.4 The underground working area of the model (without the roadways to be
developed)..............................................................................................................59

Figure 4.5 The underground working area of the model (with the roadways to be
developed in preview mode) ................................................................................60

Figure 4.6 The first development panel of the model..................................................60

Figure 4.7 The second development panel overview of the model..............................62

Figure 4.8 The updated roadway development logic...................................................63

Figure 4.9 The roadway object and parameters editor of the updated module ..............65

Figure 4.10 The parameters of each roadway object ...............................................66

Figure 4.11 The overview of the final setup of the two roadway development panels ..68

Figure 4.12 The overview of the conveyor system in the model.................................69

Figure 4.13 The overview of the conveyor system near the working faces ..................69

Figure 4.14 A close view of the conveyor system.......................................................70

Figure 4.15 The travel route of the transports.............................................................71

Figure 4.16 The underground diesel point.................................................................72
Figure 4.17 The transports parked at the pit bottom ........................................ 73

Figure 4.18 The objects that control the activity of the transports ......................... 74

Figure 4.19 The underground area material storage and transport ......................... 75

Figure 4.20 The top view of the running model ............................................... 77

Figure 5.1 The task sequences of each CM ..................................................... 80

Figure 5.2 The delay input of CM007 ............................................................... 82

Figure 5.3 The fitting results report of CM007 delays ...................................... 83

Figure 5.4 The comparison between CM007 delay sample data and the Beta distribution ................................................................. 84

Figure 5.5 The delay input of CM008 ............................................................... 85

Figure 5.6 The fitting results report of CM008 delay sample data ....................... 85

Figure 5.7 The comparison between CM008 delay sample data and the Beta distribution ................................................................. 86

Figure 5.8 The summary of the simulation results with planned task sequences ....... 87

Figure 5.9 The summary of the simulation results with modified task sequences ...... 88

Figure 5.10 The utilization of the CM ............................................................... 89

Figure 5.11 The development rate versus support time of the three cases ............. 90
Figure 5.12 The effects of miner supply on development rate ...................................... 93

Figure 5.13 The effect of the material storage distance on the development rate .......... 94

Figure 5.14 The effect of downtime and scheduling delay of material supply .......... 97
# LIST OF ABBREVIATIONS

**ACARP**
Australian Coal Association Research Program................................................................. 13

**AFC**
Armoured Face Conveyor........................................................................................................ 7

**ATRS**
automated temporary roof support ....................................................................................... 5

**BM**
Bolter Miner............................................................................................................................ 4

**BSL**
Beam Stage Loader.................................................................................................................. 8

**CM**
Continuous Miner................................................................................................................... 3

**DES**
Discrete Event Simulation....................................................................................................... 48

**KPI**
Key Performance Indicator..................................................................................................... 101

**LHD**
Load Haul Dump vehicle......................................................................................................... 4
MB

Miner Bolter.............................................................................................................................................. 3

MG

Main Gate .................................................................................................................................................... 11

MPOH

Meters Per Operation Hour............................................................................................................................. 13

MPV

Multi-Purpose Vehicle.................................................................................................................................. 33

MTBF

Mean Time between Failures ........................................................................................................................... 70

MTTR

Mean Time to Repair ...................................................................................................................................... 70

OR

Operations Research........................................................................................................................................ 40

RAL

Remote-controlled Automatic LHDs .................................................................................................................. 43

RFID

Radio-frequency identification .......................................................................................................................... 17

RTV

Rubber Tyred Vehicle...................................................................................................................................... 34

SC
Shuttle Car................................................................. 3

SCM

Supply Chain Management ................................................................. 23

SL

Stage Loader........................................................................... 11

SMV

Specialised Mining Vehicles............................................................... 58

TG

Tail Gate............................................................................ 11

USS

Under Supply System................................................................. 45
1. GENERAL INTRODUCTION

1.1. Introduction

Underground coal is mined mainly using two different mining techniques: room-and-pillar and panel-and-pillar (also referred to as longwall) mining. The most common practice used across Australian underground coal mine sites is longwall mining (Commonwealth of Australia 2014). This is due to advantages, such as:

- high extraction ratio reaching 90% in some mines,
- high productivity, a single longwall face can achieve over seven million tonnes of coal per year, and
- increased safety.

These benefits are realised by the utilization of three main pieces of equipment and the associated technologies: armed face conveyors for the transport of coal, powered roof supports for the safe working conditions and coal cutting machines for the high efficiency of extraction.

There are four critical operations (Figure 1.1) in an underground longwall mining system. These are roadway development, longwall production, gas drainage and panel changeover (Gibson, 2016).
1.1.1. Roadway development

Longwall panels initially are created by first developing roadways (also called headings) allowing the access to the coal seam and the movement of materials and equipment toward the working face, and coal away from the face as well these roadways associate work, such as ventilation and other services to the working face.

There are two types of headings in a typical longwall layout: the headings that extend from the mine underground entrance to the longwall blocks are called main headings (or mains) whereas the headings that are developed on either side of a longwall block and connected across the end of the longwall (before the extraction face of longwalls) are known as panel headings or gate roads (gateways). Mains usually consist of 5-7 headings while gateways usually have two headings (most common) or three headings occasionally on both sides of the longwall panel. These two or three gateways, with one
for materials and fresh air in and the other for coal transporting and used air out, are usually connected by a “cut-through” driven from one heading to another at regular intervals (e.g. 120m). This leaves a series of coal pillars for support. This is illustrated in Figure 1.2.

![Figure 1.2 A simplified underground coal mine system](image)

These two types of headings are developed by a continuous miner (CM) cutting and loading the raw coal into Shuttle Car (SC) (common configurations) or haulers (for the sake of a continuous haulage) to the boot end. The coal is then transported through the belt conveyer system to the pit bottom finally to the surface; usually the coal is transported by the belt conveyor system through a drift directly to the surface. A CM having the ability to cut coal and bolt in sequence is known as Miner Bolter (MB). A
CM that does both the cutting and bolting operations simultaneously is known as Bolter Miner (BM).

As these headings will be in service for months during the longwall generation and extraction processes and in some cases even years, the underground geological condition requires ground control to maintain safe underground working condition. This is the area where most of underground consumables, such as roof bolts and mesh are used.

Consumables are transported from the surface via a shaft utilising a cage hoisting system and/or a drift via a train system to underground storage areas. Consumables are then transported to development bulk store areas by transporters, such as Load-Haul-Dump (LHDs) and trailers. Materials stored in the bulk store areas are then transported to and stored at the out-by areas of headings or the cut-throughs.

One possible scenario demonstrating operational configurations and sequences in the front of a development heading is as following: first a CM is loaded with consumables and then does a cutting and bolting sequence with a cutting depth of 0.5m. The CM advances a metre after every two cuttings sequences. The ventilation tube extension is done every two metres. After every 30m or after every 24 hours operation there will be a stone dusting operation. One supplying delivery enables CM to advance 30m, which means the miner must be resupplied after every 30m. This typical operating cycle begins by tramming the CM up to the face and putting it into the cutting position. Two
to four stab jacks are lowered to the mine floor and an automated temporary roof support (ATRS) canopy is set against the roof to create a safe working place. The operation sequences of a one-pillar cycle are shown in Figure 1.3.

![Diagram of Pillar Length](image)

**Figure 1.3** The sequences of heading development

The main pieces of equipment used in roadway development are summarised below,

- Continuous Miner (CM),
- Shuttle Car (SC), and
- breaker feeder/boot end.

Whether it is a Bolter Miner or a Miner Bolter, the continuous miner is used to cut and load the coal to the back of itself, Dumping the coal to the shuttle car which is parked at the back of the continuous miner; the shuttle car then travels to the boot end after being loaded. The Feeder Breaker is used to break the coal into smaller pieces and then the coal is transported to the pit bottom by the belt conveyor system.
1.1.2. Longwall production

As a widely used mining method throughout the industry, longwall mining requires the development of each panel to be completed before longwall mining commences and the high coal production rates can be achieved.

Longwall face equipment is established at the end of the panel remote from the main headings and coal is extracted within the panel as the longwall equipment moves towards the main headings (Figure 1.4). This configuration is known as retreat mining (The reverse method is called advance mining).

![Diagram of longwall mining](image)

Figure 1.4 Typical plan view of a series of longwall panels (MSEC, 2007)
A longwall shearer is the piece of equipment used at the longwall face. It can be up to 15m long and weigh up to 90t. It commonly extricates a one-metre-cut off the coal seam face and pushes the broken coal onto the Armored Face Conveyor (AFC) as it voyages forward and backward over the board, along rails that are fundamental to the AFC structure. The AFC conveys coal to an ordinary belt transport which then transports the coal to the pit bottom of the mine and then to the surface via a shaft or directly to the surface through a drift.

As the shearer moves over the face, substantial double activity pressure driven rams connected to the rooftop bolster modules logically propel the AFC behind the shearer in a snake-like action. The AFC is then held set up while every backing is manoeuvred into the new arrangement utilising the same double activity water driven ram beforehand used to push the AFC. At the point when the shearer finishes traversing the face, it resets to take a cut as it returns back over the face and afterwards the cycle is repeated. As the longwall gear advances in this way, the rooftop material falls into the void deserted by the propelling framework. This is known as a bi-directional cutting arrangement. The four regular cutting methods and arrangements on a longwall face are:

- bi-directional cutting arrangement;
- uni-directional cutting arrangement;
- half web cutting arrangement;
- half-way opening cutting grouping.
The major pieces of equipment used on the longwall face are listed below:

- shear - cuts the coal into slices known as “web”,
- chocks - shields that support the roof directly behind the longwall face,
- armoured faced conveyor - moves the coal along the face to the Beam Stage Loader (BSL),
- BSL and crusher,
- boot end - allows for incremental retractions of the longwall face equipment.

The locations of these pieces of equipment are shown in Figure 1.5.

Figure 1.5 Longwall face equipment diagram (Hem, 2015)
1.1.3. Gas drainage

Coal seam gas, which is formed by the compression of plant matter over millions of years, consists of a combination of methane (95%) and carbon dioxide (5%). Mining activity leads to the disruption of *in situ* coal and causes the contained gas to be released into the mine atmosphere.

Removal of gas from the coal seam and surrounding strata, usually by gas drainage, must be carried out to meet the statutory limits determined by either local regulations or the national laws. These statutory limits reduce or eliminate the possibility of outbursts and create safe and comfortable working conditions for workers.

The benefits of gas drainage are:

- lessen severity of outbursts,
- reduction of downtime from gas problems,
- drained gas can be utilized for power generation,
- decreases methane emission and environmental damage.

Gas drainage can be achieved through either of two ways:

- via the mine ventilation system, or
- via drilling techniques.

Mine ventilation is normally used in mines with relatively low coal gas content. However, in coal deposits with high gas content beyond threshold limits, gas drainage
can be carried out by drilling boreholes. Drainage by bore hole drilling can be carried out either from the surface or from underground (Figure 1.6). In either case the drainage of gas can be carried out either prior to mining ("pre-drainage") or after mining of the coal seam ("post drainage").

Figure 1.6 Surface and underground gas drainage examples (Sharma, 2008)

1.1.4. Longwall changeover

Longwall changeover, which is also known as longwall change-out or longwall recovery and installation, is a major factor in the overall efficiency of a longwall operation. It utilises the operations of recovery, transport and installation. These operations are time-consuming and labour intensive, which leads to a substantial drop in
coal production and an excessive burden on the transport system (Figure 1.7). These logistical operations require detailed planning in advance and close supervision during the exercise to reduce installation and recovery time.

![Diagram](image)

**Figure 1.7 Longwall change-out critical path (Longwall Mining, 2017)**

The sequence of equipment recovery is somewhat predetermined. If only one gate road is accessible, the sequence would be in the order of the following list from top to the bottom:

- Stage Loader (SL),
- Main Gate (MG) drive,
- Shearer,
- AFC,
- Tailgate (TG) drive,
- Supports (from TG first).
An ideal case would be the situation that both gate roads are accessible. Therefore, a concurrent removal sequence would be:

- MG drive and transfer and TG drive concurrently,
- shearer, SL concurrently,
- AFC, and
- supports.

Equipment involved with modern longwalls is preferably transported as complete units if the transport system permits to reduce the chance of dismantling and reassembling. Specialized transporters are used for the movement.
1.2. Research Problem

Most of the Australian coal mines strive to achieve higher headings development rates (e.g. of 7 meters per operation hour (MPOH) or higher in the near future). Such mines all face the challenges of insufficient supplying of materials and more broadly inadequate logistics systems (Duin et al., 2011). A recent study conducted by the Australian Coal Association Research Program (Gibson, 2015) concluded that amongst the major factors that affect the efficiency/ability of the underground logistics system are extensive traveling distances, limited transportation provisions and poor floor conditions. Certain factors in the broader operating environment, for example, declining or fluctuating coal demand/prices, aging equipment and/or outdated technologies and excessive capital expenditure, place further demands on businesses to achieve sustainable improvements in mining operations. It is therefore crucial for mines to utilise their equipment with a higher efficiency and maintain the material supplying at a more sufficient and more reliable levels compared with the current system, to reduce operation costs, minimise capital expenditure and eliminate or reduce materials-supply-related heading advance delays.

The underground coal mine production system is a dynamic, complicated and space limited system. It includes subsystems such as longwall coal extraction, development unit advancement and transportation of materials, personnel and coal. Gibson et al (2005) have identified that the logistics of supply, transport, distribution and handling of
such consumables as roof and rib support materials, is an issue at older, extensive mines these days. They also pointed out that for most mines to achieve a higher development rate they will encounter similar issues. Therefore, how to maintain a sustainable logistics system efficiently and reliably is a challenge for Australian mines, especially when we consider that a high roadway development rate in the future is accompanied by a high material consumption rate. This high consumption rate correspondingly needs a high replenishment speed (short lead time) or a high transportation and reaction ability. However, underground roadways are space-limited, which leads to the transportation and storage abilities being limited and transport speed restricted. In reality, a larger capacity often means a larger equipment size which is not permitted due to the roadway sizes; more transporters underground, as stated in one of ACARP’s Industry Survey Reports (2015), means more diesel particulate matter (DPM) generated by these diesel-powered vehicles however the level of density of DPM in tunnels is restricted by the ventilation requirement. Therefore, it is necessary to study the ability and reliability of the current logistics system through the way of simulation without affecting coal production system to highlight the system constrains and potentials.

Although it is generally acknowledged that both longwall production and roadway development rates can be severely constrained by the capacity and capabilities of the logistics system, no systematic studies have been undertaken to investigate the relationship between underground logistics systems performance and mine productivity.
This may primarily be due to the difficulties associated with grasping the inter-relationships among the large number of variables at play in underground mining logistics systems. Therefore, there is a clear need for developing a better understanding of the structure and functioning of existing logistics systems to identify the relationship between the logistics and roadway development rate, to aid optimisation efforts improving the ability and reliability of the logistics system.

Traditional ways, e.g. mathematics modelling, are impractical to deal with complex realistic system (Thierry et al., 2010). Simulation has been the popular approach to identify a system’s bottlenecks and help to make strategic decisions. Therefore, in this thesis, an underground mine logistics simulation model which is based on FlexSim simulation software is developed to analysis underground coal mine roadway development logistics system. Such a model can offer useful guidelines for system optimization in an integrated production background.
1.3. **Aim and Objective of the Thesis**

The aim of this research is to develop a simulation model as a tool to holistically analyse the impact of coal transport and materials supply on the roadway development, to identify bottlenecks and finally, with the combination of logistical strategies and methodologies, offer possible solutions and system improvement.

A logistics model was developed based on a roadway development simulation model by Cai (2015), which simulates the roadway development activities without logistics. The supposed model was developed using a general-purpose simulation package, FlexSim and configured with input data collected from one of Australian underground coal mines. Cai (2015) simulation model was refined and validated using historical performance data collected from an operating coalmine site. Sensitivity analysis was done using a modified model to identify bottlenecks/constraints and highlight production potentials of the logistics part of the roadway development by the following ways:

i. identifying the deficiencies of the existing logistics system (e.g. process bottlenecks, delays/lost time, resource/equipment utilisation issues and scheduling problems);

ii. evaluating alternative process improvement initiatives (e.g. addition of resources, application of improved methods and the use of more efficient scheduling algorithms);
iii. assessing the impact of adopting new technology or alternative transport/infrastructure systems (e.g. monorails, battery-powered vehicles, robots, drawn technology, radio-frequency identification (RFID) and concrete roadways); and

iv. examining the interplay between logistical system capacity and future expansion or growth strategies (e.g. production capacity, infrastructure upgrade and mine expansion).
2. ROADWAY DEVELOPMENT AND THE LOGISTICS

2.1. General

2.1.1. Development methods

In Australian underground coal mining practice, roadways are created first for the longwall panel creation. There are two main options of roadway development, namely, the place-change method and the in-place method.

For the first option, a conventional CM and a Roof Bolter (RB) are used together: when the CM advances a certain distance, typically 5m and then moves to another heading, it leaves an unsupported area of roof. The RB then supports the roof of the previously mined section. The maximum depth of each cut is limited by the geological conditions and the Australian coal mine safety laws; in this case the roof must be competent. As the width of the heading is greater than the cutter head, the CM must change position to mine the full entry width, in other word, the CM works in a two-pass mode. For the most common practice in Australian mines, the miner is equipped with roof bolters and cuts the whole width of the entry in one single pass.

The Miner Bolter (MB) conducts non-concurrent cutting and supporting in sequence and the Bolter Miner (BM) conducts concurrent cutting and supporting cycles in parallel. BMs are generally much quicker because they cut coal in parallel with the support operations, which maximises the speed of advance.
2.1.2. Development sequences

Figure 2.1 is an example of a mine plan for the roadway development advance sequence using one CM. The left-hand heading is developed first by continuing into the overdrive of the next pillar cycle heading (Sequences 1 and 2 in the Figure 2.1), followed by driving the cut-through (Sequence 3) and then the right-hand heading to its overdrive (Sequences 4 and 5). These cutting sequences are constrained by aspects of ventilation, coal and material handling, roof conditions, etc.

Figure 2.1 Cutting sequences of a two-heading roadway development (Birchall, 2007)
During these processes, there are other tasks that need to be done as well, based on the distance driven, for instance, installing the service range, installing the tell tales to monitor the roof strata subsidence, installing extra supports, stone dusting, cutting niches for storage and widening the roadway. Because of changes in the geometry and geological conditions, and consequent changes to the support plan for different sections, the cutting time per web is not always the same during each pillar and can differ from pillar to pillar.

There are also the cases that two CMs are used in two headings at the same time and there are cases that three or more headings that need to be developed utilizing different cutting sequences.

2.1.3. Roadway support

In order to ensure the stability, ground control must be progressed using the mechanical or resin grouted roof and rib bolts, usually in combination with mesh sheets (Figure 2.2). They are usually installed with bolting rigs which are mounted on the CM within 1-3 m of the immediate face. When it is necessary roof straps and cables are also used.
Roof bolts which are chemically anchored with the typical length from 1.8m to 2.4m long are installed at densities that range from two to eight bolts per metre. In some cases, long tendons (4-8m) are also installed as part of the primary face support cycle. Chemically anchored rib bolts that range from 1.2-1.5m long are installed at densities ranging from two to six bolts per metre. The rib mesh sheets are typically 5m long and 1.2m wide and are overlapped by 200mm in the majority of Australian longwall mines; rib mesh sheets are usually applied on both sides to prevent rib spall, typically from the
roof to half seam height or at around the mid-seam. Figure 2.3 is an example of the support plan in one Australian coal mine.

![Figure 2.3 Roadway roof and rib support plan (Birchall, 2007)](image)

The support plan varies as the roof and rib conditions change; therefore, several plans may be used while just developing one longwall panel. For example, there may be double bolts density used when the roof condition is bad (such as faults) when compared with good roof condition. Therefore, the materials consuming rate may increase which puts the pressure on the transport system.
2.2. Logistics in Underground Coal Mines

The terminology of logistics itself comes from the late 19th century (Tepić et al., 2011). It is the management of the flow of things from the point of origin to the point of consumption, The context of which involves planning, implementing and controlling the material flow in a systematic, efficient and effective way to enhance the organizational performance of a system (Bowersox et al., 2002). It is one component of supply chain management (SCM). The domain of logistics management, therefore, consists of the following key elements within the organisation (Hallock, 2010):

- transportation network design and management,
- warehousing techniques, including location design and management,
- materials handling management,
- system-wide inventory management,
- order management and fulfilment, and
- procurement.

From a logistic perspective, a coal mine can be considered to be a vast materials handling system, which could, in turn, be roughly divided into two subgroups according to the geological locations where logistics operations take place, namely, surface logistics and underground logistics.
Surface logistics issues may include: the design and operation of coal transportation networks from pit to port, as well as the management of materials and supplies movement from multiple sources (vendors) to surface storage locations.

However, from a broader supply chain management perspective, surface logistics may also include the selection of suppliers, transporters and storage locations, as well as determining the capacity of various facilities involved.

By comparison, underground logistics operations involve the transportation of coal, material supplies and personnel, electrical distribution, communication system, water handling system and hydraulics, ventilation and logistic panning which entails:

- transportation of coal (Figure 2.4), rock, personnel, consumables (Figure 2.5), equipment, etc.,
- warehousing of materials (cables, bolts, meshes, etc.), including location design and management,
- materials handling management.
Figure 2.4 Transportation of coal by belt conveyor

(Conveyor System, 2017)

Figure 2.5 Underground mining logistics supplying system
The scope of this study will focus on underground materials supply logistics from the pit bottom to the development headings and the reverse logistical operation of coal transport from roadways, the content of which are summarised in Figure 2.6.

![Logistics within mines](image)

**Figure 2.6** The main components of logistics within a mine (Kiriden, 2017)

Mine constructions, gas drainages, electrical distribution and communication systems are also considered as part of an underground coal mining logistics system. However, those were not considered in this study as this thesis focused on the direct impact of logistics on the coal production.
All of these sub-systems are summarized in Figure 2.7, which is a modified version of Miwa and Takakuwa (2011).

Figure 2.7 Integrated underground logistics system (Miwa and Takakuwa, 2011)

2.2.1. Sub-Logistics system of coal transportation

Coal from underground is mainly from longwall production, which accounts for around 90%, with the balance from the heading development (Gibson, 2015).

Coal extracted by shearsers at the longwall working face is loaded by the AFC (Figure 2.8) to one side of the longwall face and then transported by the belt conveyor via the belt road to the main transport systems. This efficient system provides continuous
haulage from the working face to the pit bottom or directly to the surface. A mine with a
drift or adit access requires a conveyor transport system to the surface while a mine with
shaft access requires hoisting system of coal in the shaft.

![Armed Faced Conveyor (AFC)](image)

Figure 2.8 Armed Faced Conveyor (AFC) (Underground coal, 2017a)

Options (Figure 2.9) available for haulage of coal from development production faces
are:

- shuttle car,
- battery or diesel-powered coal haulers, and
- continuous haulage system.
In Australian coal mine practice, the SC is still the primary means of transporting coal from the CM to the panel conveyor in development units. It provides a batch and not a continuous haulage system with the flexibility of being able to quickly and easily withdrawn from the face roadway and to be used for transport of bulky materials such as ventilation ducting. This electric powered, rubber-tyred vehicle has been proved to provide a robust, flexible and generally reliable haulage system.
Battery or diesel powered coal haulers are a possible alternative to the SC and they offer the following advantages when compared with SCs (McKendry et al., 2009):

- no trailing cable with the associated arcing/ flashing risk,
- no cable to restrict tramming distance,
- carry greater payload, and
- better seating arrangement and ergonomics for operators.

Continuous haulage systems are designed to accept the CM conveyor output and discharge at this rate onto the panel conveyor, which means eliminating the delays inherent in the SCs’ and haulers’ batch haulage systems (McKendry et al., 2009, Golsby, 2012).

The feeder-breaker (Figure 2.10) used between shuttle cars and belt conveyor system in the development units plays such a role by removing peaks from coal flows and allowing lower capacity in the outbye belt systems.
2.2. Sub-logistics system of material and personnel transport

As the highly concentrated materials storages are underground, a large number of materials are transported in bulk or kit from the surface either via the shaft or the drift into the headings by different types of vehicles to support the heading operations and thereby guaranteeing the required advance rate.

These materials used in the roadway development are:

- strata support materials (roof and rib bolts, washers, chemical anchors, long tendons, W straps, mesh and cans for development units),
- tradesmen’s tools and mining machinery spares,
• section crib room and emergency escape equipment modules,
• lubricants, picks and spares for mining equipment,
• fuel for diesel powered equipment,
• limestone dust for treatment of mine roadways,
• road base for repair and construction of mine roadways,
• trailing cable for mine equipment,
• conveyor belt and structure,
• pipes for water, pumping and compressed air supply, and
• miscellaneous items of equipment such as tyres, chains, tracks, motors pumps and transformers.

Mesh and bolts are often supplied in different sizes and numbers for different locations. These differences may be due to the different entry sizes and/or different geological conditions even in the same entry but at different distances. Ventilation tubes are used at a certain distance for the purpose of ventilation to create working conditions that are good for workers’ health and the safety of the mine. Stone dusting is used for the prevention of the propagation of coal dust explosions throughout their underground mines in Australia.

These materials, purchased from and delivered by suppliers, are initially stored in the surface warehouse. Materials are then carried by the way of bulk feeding in pods (special purpose applications for roof support materials, crib rooms and stone duster), or
Kitting in cassettes (for roof bolts, cartridges, washers, chemical anchors and butterfly plates) or trailers on flat top rail trolleys and finally towed away at the end of rails by a rubber-tyred multi-purpose vehicle (MPV) (Figure 2.11) or load haul and dump (LHD) to the designed spaces. The pods commonly used for underground roadway development have been summarized in the Figure 2.12.

![Figure 2.11 Multi-Purpose Vehicle (MPV)](image_url)

Figure 2.11 Multi-Purpose Vehicle (MPV)

(Plant miner, 2017)
Figure 2.12 Materials handling pods for different materials (Macquarie Manufacturing, 2017)

Well organised logistical operations should be able to minimise the materials related roadway development delays.

Transport systems for personnel and materials are largely determined by the mine access modes (e.g. shaft hoist for vertical shaft and drift haulage for decline drift respectively with transfer to the diesel powered, rubber tyred vehicle (RTV) being used at the pit bottom for the majority of mines in Australia). In mines with a drift, where rubber-tyred transport from surface is not practical, rail transport with a haulage winder is the norm. This vehicle is typically used as a means of attaching other rolling stock to
the winding rope and, if set-up to carry passengers is usually referred to as a "dolly car" (Figure 2.13). A dolly car can be automatic (push button control by the passenger) or operated by an on-board operator, particularly where the dolly car is utilized to haul other rolling stock into and out of the mine. Dolly cars typically have limited capacity for passengers and additional personnel carriage(s) are attached at shift changeovers to enable the full shift to be transported in one load or lift.

![Figure 2.13 Dolly Car fitted for man riding and connecting to materials transport cars](image)

(Underground Coal, 2017b)

At the pit bottom, most mines within Australia use Load Haul and Dump (LHD) Quick Detachable System (QDS) (LHD-QDS) attachments (Figure 2.14) to load consumable pods (Duin et al., 2011). This versatile system enables the easy movement and replacement of attachments for specific purposes and generates the systematic flexibility and has replaced the rail transport system which was the dominant system in the past.
As for the transport of personnel, a specifically-designed vehicle is used in and around most mines. It has the ability to transport the whole crew (10-12 miners) for one shift, through the mine to the coal face where their work is carried out and then brings them back at the end of their shift (Smith et al., 2010). This vehicle can also be used for other purposes, such as transporting light equipment within the mine. One type of vehicles is shown in Figure 2.15.
2.2.3. The “customer” in mine logistics systems

Coal mines, as the suppliers of nature resource of coal, also play the role of a customer in a supply chain system to support coal-cutting-oriented operations and guarantee a continuous supplying of coal for the market, whether it is domestic or abroad.

Most of the materials periodically used at the roadway development face are located in the roadway development sites for the support of roadway development. Materials, such as, mesh, bolts, ventilation tubes are “consumed” by CM.

The CM was developed to meet the increasing demands put on roadway development in underground coal mines in Australia in the early 1990s. It is a machine with direct drives to power cutting, traction, gathering and hydraulic systems. A CM cuts a square or rectangular profile roadway known as the first workings in a coal mine. The cut coal
is gathered and conveyed though the centre of the CM and then transported by shuttle car to the boot end.

There are two main manufacturers that supply CMs to Australian underground coal mines, namely Joy Global and Sandvik. These two manufacturers build many different models that are suited to different purposes and conditions. The manufacturer and model of a CM is selected primarily on the cutting width and height that the CM was designed for. The drum diameter that is used on the CM is an important factor as it dictates the depth of cut. Both Joy Global and Sandvik miners are capable of cutting and bolting simultaneously as the cutting and loading functionality moves relative to the fixed body.

Figure 2.16 shows a typical CM machine which does not have bolting rigs attached.
A BM combines a roof and rib-drilling machine and coal cutting. It drills and bolts while it cuts and conveys coal to the rear of the machine. The key feature is the sliding frame, which allows simultaneous mining and bolting (Figure 2.17).

Figure 2.17 MB450 Bolter Miner by Sandvik

(Geotechpedia, 2017)
3. MODELLING LONGWALL MINING LOGISTICS

Although logistics management is a mature discipline area and has been successfully practiced in a variety of industry settings over a long period of time, research and its applications in the mining industry are rather limited (Strang, 2011, Gamache et al., 2004b). The vast majority of logistics research in the context of mining has focused on the surface logistics (e.g. optimising pit-to-pit supply chains) and open-pit mining (e.g. scheduling of haul truck dispatch), with limited studies in the area of underground mine logistics. However, a number of recent industry-based studies, as well as scholarly literature, have highlighted the significance of underground coal mining logistics, in light of changing market conditions, large capital expenditure involvement and ever-increasing distances from the mine surface to the working faces (Lala et al., 2015, Feng and Zhao 2010, Gibson, 2005).

The limited literature available in the area of underground mining logistics can be broadly classified into Operations Research (OR) based studies and simulation modelling-based studies. OR techniques have long been used in logistics, with applications to underground mining predominantly in transportation and fleet management problems, for example: dispatching, routing and scheduling of load-haul-dump (LHD) vehicles (Gamache et al., 2005), balancing production and haulage operations through the use of temporary storage solutions (Kuo and Yang, 2011); and the improvement of material flow and the reliability of logistics systems.
(Beamon, 1999). By comparison, simulation studies have widely been used for: the evaluation or selection of alternative transportation/materials handling technologies and methods (Fioroni et al. 2014, Salama et al., 2014); studying the dynamics of traffic flow and/or haulage operations (Greberg et al., 2016, Zeng et al.,2017); as well as assessing and optimising alternative production logistics systems (Anani, 2016, Feng et al., 2010).
3.1. Operation Research Based Studies of Underground Mining Logistics

Research on underground mining transport dates back to the early days of the application of simulation to computer science (Fioroni and Seixas, 2014). A simulation study of an underground railroad in a coal mine was done by Hayashi and Robinson (1981), aimed at achieving best train configurations and dispatching strategies with minimum resources, to sustain coal production. Another study by Huang and Kumar (1994), dealt with the optimisation of the number of vehicles deployed in an underground hard rock mine using queuing theory (Figure 3.1), for a given production block to meet its production target. The complementary strengths of the two mathematical approaches used in their work, were that they were able to account for the dynamic features of a mine system, such as, equipment idle times, as well as some economic factors (operator’s salary, maintenance cost etc.). However, inherent limitations of an abstract mathematical representation (Cooper, 1981) of a complex underground mining system, mean that the number of variables and their interactions that could be studied were quite limited.
Figure 3.1 The queuing system of LHDs, production blocks and repair shop

(Huang and Kumar, 1994)

A significant proposition of the OR-based studies has focused on the fleet management problem. For instance, Vagenas (1991) discussed the management (dispatch and traffic control procedure) of remote-controlled/automatic LHDs called RALs in an underground mine, to support the proposition that tramming and dumping operations should be automated while loading should be controlled by an operator through a television system. The shortest path algorithm was used in this study to select the destinations for RALs. This approach considered the “interactions” between different RALs, for example, the shortest available path, the possible slowing down or stopping
in certain traffic zones, or in the case of a conflict in a bi-directional section. The second module in their method used heuristic procedures to identify a destination for a RAL.

Gamache et al. (2004a) also used a similar vehicle-by-vehicle approach and their method also included a shortest-path algorithm. The solution was inspired by the method proposed by Kim and Tanchoco (1991) and some concepts of graph design presented by Vagenas (1991) and Krisnamurthy et al. (1993). The key elements of this approach included the identification of time-windows where intersections and road segments are free and the construction of a time-windows based graph followed by the selection of the best conflict-free route for the vehicle based on this graph. An extension to this work has been done by Beaulieu and Gamache (2006) by complementing it with a dynamic-programming-based global approach to select the best routes for all vehicles. They proposed a new and more efficient formulation of the states to deal with the displacement mode, which is not covered in Gamache et al.’s (2006) earlier work.

In a somewhat different line of research, Lan and Qiao (2011) analysed the relationship between coal bunker availability and production logistics reliability in underground coal mines. This research was based on the producing layout underground. By way of building, analysing, calculating and comparing a reliability model of the system and with the use of a reliability calculation formula of a coal bunker, the authors concluded that the establishment of a coal bunker is an effective way of enhancing the reliability and improving the balance in the production logistics system.
One of the few early coal mining logistics work was undertaken by Muguira (1998) which was called the ‘under supply system’ (USS) to improve the productivity and the overall system performance. His work was based on Australian coal mine practices and a review of thirty underground coal mines for identifying potential improvement opportunities within the supply and materials handling functions.

Muguira’s work (1998) recognises the functions of the underground logistics system as a whole, paying particular attention to the physical, control and information sub systems. Its content addressed the needs to integrate the functions of multiple departments within a mine. Thus, the author advocates a holistic and multi-disciplinary approach to dealing with logistics issues with a view to improving mine productivity and performance.

Subsequent studies have followed an approach similar to what was advocated by Muguira (1998) in that they have dealt with a substantial portion of the logistics systems. Mondring and Berger (2014) applied a Tracking and Tracing System (TTS) to collect and monitor underground logistics systems to improve the transparency throughout the whole transportation chain. Equipment and/or subsystems utilised for in their study included:

- Personal Digital Assistants (PDAs), used by employees to collect and transmit required information;
- fibre optic cables, for data transfer;
• the application of ProNet for surveyed data assimilation and visualized by a 3D-model;
• Transport Steering Software (TS/4), for supply schedule, and
• Material Tracking and Tracing System (T&T).

This system is illustrated in Figure 3.2.

![Figure 3.2 Transport planning, steering and material tracking & tracing](Mondring and Berger, 2014)

The application of this system had led to a significant transparency and improvement of the transport system in a working day.
Similarly, Shan et al. (2012) have developed a logistics management system to monitor, collect and manage underground logistics information. This system adopted the Radio Frequency Identification Technology to monitor vehicles’ and materials’ location information and transfer this information to the surface through wireless technology.
3.2. Simulation Based Studies of Underground Mining Logistics

Simulation, in its capacity as an enabling technology (Crosbie, 2000), has been widely used to solve logistics problems and to support decision making (Sargent, 2011) in such diverse forms as process description, “what-if scenario” analysis and bottleneck detection.

Several studies have used simulation tools to visualise and understand the dynamics of underground mining logistics systems, as well as analysing and evaluating them for improvements. For example, Feng et al. (2010) have highlighted the need for studying what they called the ‘production logistics system’ to improve underground coal mining operations from both economic and safety perspectives. To this end, the authors advocated a comprehensive approach which included the development of a simulation model using the software tool WITNESS to identify bottlenecks in the logistics system. Following the discrete event simulation (DES) logic and queuing theory, Feng et al (2010) focused on modelling and analysing the whole transportation system – from shearer cutting to the surface in order to identify the relationship between shearer cutting speed and the output of working groups, and the relationship between the speed of each run-time links and the working face production level. The supply system was not wholly included in the simulation model. Feng and Zhao (2010) illustrated the structure and characteristics of such a logistics system in some detail (Figure 3.3).
Other studies have used ARENA simulation tool to support similar studies with the exception that the authors have concentrated on sub systems of the entire underground logistics system. Miwa and Takakuwa (2011) built material handling system of an underground coal mine using ARENA to study the relationship between the material handling system speed, storage bin capacity, production rate and the bottlenecks of the
logistics system. An ARENA-based simulation model was also used by Pop-Andonov (2012) to analysis the underground haulage system. This model described a hypothetical mine with the main goal of analysing cost and time of the track and rail transportation system. The work by Fioroni et al. (2014) can be described as an extension to the work undertaken in the above studies. Their model considered more complicated conveyor networks under four different scenarios with the goal of finding the best layout option to achieve the scheduled production rates using the lowest investment in trucks, instead of just analysing a pre-defined system with a simple layout.
3.3. **Synthesis of Underground Mining Logistics**

This detailed literature review reveals that, albeit slow progress, research into underground mining logistics has made some useful contributions in terms of clarifying the concept of logistics in the context of underground mining and advancing the understanding of the relationship between logistics and production systems. The review also highlighted that research has progressed along two tracks, namely OR techniques in general and simulation modelling in specific. Researchers have used different tools such as simulation models to deal with different aspects of underground logistics (e.g. underground storages, fleet management and network design), but with the common purpose of identifying issues and improving performance. These efforts align with Strang’s (2011) observation that the requirement is to match the techniques with the research goal and data type as there are many techniques available to deal with logistics issues.

Underground logistics, whether hard rock mining or coal mining, constitute integrated systems consisting of different material handling, materials/personnel/equipment movement, information flow and activity/operations control sub systems (Feng et al., 2010). Studying and optimising these sub systems separately, without considering the often dynamic and complex interactions among them, may not account for the system attributes and behaviour in their entirety and therefore the identified problems and proposed solutions may not yield desired results. This situation calls for further work to
develop methods and tools to examine these subsystems and the relationships between them from a holistic perspective.

Additionally, it is reported that the mining industry worldwide has experienced a productivity decline, estimated to be a significant 28% over the past decade (Lala et al., 2015). Furthermore, coal mining in Australia is currently undergoing a period of transition from a high-demand and high-commodity price operating environment to a low-demand and changing commodity price operating environment. Against a backdrop of large scale capital expenditure afforded during the mining boom, declining productivity and the effects of changing market conditions, the industry is now demanding more efficient strata support materials handling and supply systems (Gibson, 2015).
4. DEVELOPMENT OF THE DISCRETE EVENT SIMULATION MODEL

4.1. The Roadway Development Module

A discrete-event underground roadway development simulation module, MINESIM (Figure 4.1), developed by Cai (2015) using FlexSim software was used as the basis of this thesis. MINESIM was structured such that it can be configured to most underground coal mine roadway development layout with development operations matching Australian mining practices. The module can run many replications of multiple scenarios with multiple sets of variables such that the full range of mining processes, including random and variable delays, can be integrated into a single, best practice simulation platform that enables an entire processing chain to be analysed and improved in context.
MINESIM module has the ability to simulate the following machine combination groups and allows any number of the groups to be simulated in one scenario:

- one CM with one SC;
- one CM with two SCs;
- one CM with continuous haulage system; and
- two CMs with two SCs.

MINESIM offers sensitivity analysis tools for evaluating the impact on roadway development rates of various aspects of the operations (Figure 4.2). The parameters include:
• pillar and cut through dimensions;
• mining sequences;
• number of entries;
• number of mining machines in use;
• miner type (bolter miner or miner bolter);
• cycle times for cutting and loading at the development face;
• coal clearance system utilised;
• SC capacity, tramming speeds;
• cycle time for discharging of a SC;
• roof/rib bolting rigs utilised;
• roof/rib support density;
• bolt type;
• continuous haulage system utilised;
• shift roasters;
• panel advance delay;
• duration and frequency of stone dusting, supply miner, extend vent tube, etc.;
• install long tendon/tale-tell length/density/delay;
• machine breakdowns;
• delays of gas drainage, cut niches, widen roadways;
• cut breakaway and holing through;
• relocation of mining machine;
• delays affecting outbye services; and
• delays affecting face operations.

Figure 4.2 The capacity of the roadway development module (Cai, 2015)

According to Cai (2015), MINESIM module has the following features:

• “The module is object oriented with 3D objects. It performs in a virtual reality environment. Each object works as a real piece of roadway development equipment and all the objects work together as a roadway development system.

• The configurable and structured module design with optional strategies and user-friendly GUIs makes the model easy to use, and advanced knowledge of FlexSim is not needed.
• The model can simulate any roadway layout by clicking and changing the values of the width and length, and it is flexible enough to simulate multi-heading panels by using the task sequence table.

• The module can simulate different miner types and complicated development sequences by configuring a numerical table.

• The module is flexible enough to configure any face operational delays.

• The design of the support cycle makes it possible to configure any support type, and multiple support types can be applied in different sections of one pillar.

• Multiple haulage strategies such as one SC, two SCs, or CHS can be applied and real time SC interactions simulated.

• Using the integrated analysis tool of FlexSim means multiple scenario experiments can be performed.”

MINESIM was used as the base model to further develop an underground longwall mining system in Queensland. Figure 4.3 shows the overview of the model in FlexSim development mode. The layout was based on the real mine layout. The modified CAD file was imported using the FlexSim’s background tool and the functioning modules were developed according to the CAD file. The final model consists one longwall production system, two development panels, in addition with one conveyor system to transport the coal from longwall and development faces to surface, Specialised Mining
Vehicles (SMV) Driftrunner to transport miners between the working face and pit-top and LHDs to transport material, coal and machines across the mine along setting routes.

Figure 4.3 Overview of the model in FlexSim working mode

The simulation run parameters were set up using data collected from the mine. The mine pillars are non-standard pillar layouts; the roadway dimensions, the conveyor length, the transporters traveling routes were set accordingly. The detailed model inputs will be discussed in the experiments in Chapter 5.

Figure 4.4 shows a closer view of the underground working area of the model with a longwall production system and two development systems. While Figure 4.5 shows a similar layout area with the roadways to be developed in preview mode. In the figures, the red blocks indicate Driftrunners while the green blocks indicate LHDs.
Figure 4.4 The underground working area of the model (without the roadways to be developed)
Figure 4.5 The underground working area of the model (with the roadways to be developed in preview mode)

Figure 4.6 shows the first development panel of the two panels that was modelled in more details. The development panel has been changed from three headings to two headings about half way along the longwall panel to boost the advancement rate of the development process. In this panel, there was one CM and one SC, one Driftrunner parked along a roadway, the boot end (breaker-feeder) which was linked with the conveyor, a LHD at the end of the middle heading, and other model elements.

4.1.1. The updates of the roadway development module in this project

In this thesis, two roadway development panels were developed in the model according to the layout plan from the mine. The roadway development module has three major updates: the labour transport, the outbye conveyor and the roadway parameters and logic design.
In the roadway development module, the labour availability was set using the time-table module of FlexSim, which basically assumed the labour is always on time. In this project, two Driftrunners were programmed to transport labour from the surface to the working face every 8 hours. The development activity starts 15 minutes after the arrival of the Driftrunner and stops after 8 hours counting from the time when the Driftrunner leaves the surface (8 hour working time of each shift). The production is then restarted by next arriving Driftrunner as the cycle loops in every 8 hours.

The change to the conveyor system was to connect the panel conveyor to the conveyor system which transports the coal all the way to the surface. In the old model, which simulates the panel only, the panel conveyor is not connected with any other conveyors but ended up with a FlexSim Sink object to collect all the coal items from the conveyor.

Figure 4.7 shows an overview of the second development panel model.
Figure 4.7 The second development panel overview of the model
Figure 4.8 shows the overall logic of the roadway module.

Figure 4.8 The updated roadway development logic

One of the limitations of the module developed by Cai (2015) is that MINESIM can only simulate standard roadway layout with straight parallel headings with the pillar sizes (Figure 4.1). As the roadway object is the fundamental object, the whole logic of the roadway object was redesigned, as well as part of the CM, the SC and the boot end to ensure that the roadway object is associated with the development task sequences and the SC travelling routes.
4.1.2. The redesign of the roadway object

The idea of the new roadway object is based on the fact that, the roadways are made of pillars that consists of many small sections of different parameters and properties in common. For example, each section has its own start position, section size (length, height and width), required time of each cut depth, support pattern, frequency of face operations, etc. Those parameters could be different for example looking at the start position; while some could be all the same, for example, the cutting rate could be all the same for a range of sections. A serial of sections makes one pillar. Then the sequence of the sections for the pillar defines the sequence of the sections to be developed by the miner. You can also define the parameters for each pillar, for example, how many headings of the pillar, which heading the boot end locates, the distance from the boot end to the cut through, the length of the pillar, etc. If the pillar has different layout, then you have to define the SC travelling route for each pillar.

There are pillars that may have all the same parameters except for the position. Then you can set the repeated pillars to be repeated for a certain number of times. Sometimes the pillars might be repeated in a group of two or more, and then you can define a group of pillars that consist of two or more and let the group of pillars repeat for a certain number of times.
Figure 4.9 shows the redesigned roadway object and its parameters editor based on the idea discussed in Section 4.1.2. Through the editor, you can define almost any parameter of the roadway development process and preview it in the 3D view.

The parameters are stored in the labels of each roadway object and structured properly (Figure 4.10).
Figure 4.10 The parameters of each roadway object

There are several other parameters designed for logic control and stored with each pillar, each group and each roadway object, which keep records of the development progress. Those parameters are the current roadway object, current repeating group number and rank, current repeating pillar number and rank, current section rank and current metres developed. The logic is, when every cutting and load completes, increase
the current metres by the cutting depth; if the current metres is great or equal than the set length of the current section, then increase the current section rank by 1 and set the current metres to be 0, which indicates the simulation is starting a new section; if the current section rank is greater than the total number of sections of the current pillar, than increase the current pillar repeating number by 1, and set current section index to be 1 and current metres to be 0, which means to start repeating for another pillar; so on so forth… otherwise, the logic pointer only repeats new loops cut, load, support, etc. Once all the tasks of the targeted roadway object are completed, the logic pointer moves to the next roadway object that is connected to the completed roadway object. If the next roadway object exists, then it repeats the process to complete the linked roadway object; otherwise it stops. With this new idea, the roadway module has the capacity to simulate roadways of any layout and parameters. Figure 4.11 shows the overview of the setting layout of two development panels to be simulated in this project.
4.1.3. **The updates of other objects of the roadway development module**

Similar to the newly designed roadway logic and parameter data structure, the logic of the CM, the SC and the boot end were updated as well. The updates were mostly the references link to the new data, as the old module can only simulate one pillar and repeat. And also, the logic discussed above was also updated for each object.

Figure 4.11 The overview of the final setup of the two roadway development panels
4.2. The Conveyor Module

The conveyor system utilized the same conveyor object developed by Cai (2015) for the longwall main conveyor. The speed set for the conveyor from the surface to the working faces in the main gate roads is 30% faster than the longwall main conveyor. Figure 4.12 through Figure 4.14 show the developed conveyor system of the model.

Figure 4.12 The overview of the conveyor system in the model

Figure 4.13 The overview of the conveyor system near the working faces
As the downstream conveyor always has a larger capacity than that of the upstream conveyor, the conveyor system doesn’t have any effect on the output of the model unless a breakdown occurs. However, in MINESIM modules, breakdowns could be set using the MTBF/MTTR module of FlexSim.
4.3. The Transport Module

The travel route was set using the FlexSim Network Node object. As shown in Figure 4.15, the route was set from the pit bottom to the longwall panel and the two development panels. The route was extended from the longwall face to the end of the mined area of the longwall panel. This part of the route is for the inspection access for managers. The route is made of black points and lines between the points. For each line between two points, the speed limit can be set. In this model, the speed limit was set to be 40 km/hour in the main gates, 20 km/hour along the panels and 5 km/hour at corners.

Each transport was either directly linked with a network node or a dispatcher that is linked with a network node.

Figure 4.15 The travel route of the transports
A diesel refuelling point was set at about the middle of the underground workings (Figure 4.16). All underground transports refuel at the diesel point after travelling to fill up whenever it travels more than 100 km.

![Figure 4.16 The underground diesel point](image)

Figure 4.17 shows all the transports parked at the pit bottom, while Figure 4.18 shows some of the objects that control the activity logic of the transports. As shown in the Figure 4.18, the following steps are to simulate the logic that the Driftrunners transport the miner from the surface to the working face:

1. a source object creates items associated with the task settings;
2. the items queue in the queue object if there is no available transport, otherwise it will be delayed for a setting time at the processor;
3. then a transport comes, picks it up and transports it to its destination according to its task type;
iv. at the destination, there is another processor which accepts the task if the processor is available. The processor accepts the task and starts the process for a setting time then starts the development process if the processor is at the development panel.

If the processor is not available, which means the last shift is still working, then the transport waits there until the processor is available. When the process completes the set time delay/processing, it releases the task item and stops the working panel until another new task item arrives from the surface. The frequency of the task item was set to be one in every 8 hours for each working panel to simulate each crew of 8-hour working shift.

There was a special setting for the manager’s Driftrunner. The manager goes to underground twice a day and inspect each of the three working faces and the end of the longwall goaf for one hour. However, those inspections don’t affect the production operations.

![Figure 4.17 The transports parked at the pit bottom](image-url)
Figure 4.18 The objects that control the activity of the transports

Similar logic was set for the materials. However, instead of a processor object, a queue object was used to store the task items, which have a number label indicating the amount of materials. In this case the task item is firstly sent to an underground storage queue (Figure 4.19). There is one underground LHD for each working panel that continuously transport task items from the storage queue to the panel storage queue.
Figure 4.19 The underground area material storage and transport

As the mining progresses and the materials are consumed, the number of respective item is reduced. Whenever the number reaches 0, the task item will be sent to a sink (destroyed). The mining operation stops if there is no task item in the panel queue; it resumes only when a new task item arrives. This is how the material supply was modelled.
Figure 4.20 shows the top view of the running model. In the running (presentation) mode, the logics and FlexSim links were hidden.
Figure 4.20 The top view of the running model
5. EXPERIMENT AND ANALYSIS

Underground coal mine roadway developments need to be completed on time within targeted time frames in order to get ready of next longwall panel before current longwall is complete. Resources, e.g. operators, continuous miners, shuttle cars, all need to be highly utilized in order to achieve the development rates that the mine demands. Using a discrete simulation model to simulate the mine’s development, a number of asset management issues can be investigated:

- identify bottlenecks and the effect of purchasing/hiring additional equipment.
- develop delays due to equipment downtime and effects upon maintenance improvements.
- evaluate best shift schedules to meet development rate demands.
- identify critical paths and critical start date in development projects.
- verify development schedules.

The model was then used to study the production performance using input data collected from mine sites. The field data were analysed and summarized to configure the model. This study was done to the two-heading roadway panel only.
5.1. Basic Model Input Parameters

The model input parameters were summarised in the table below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pillar length</td>
<td>125.7m</td>
</tr>
<tr>
<td>Pillar width</td>
<td>71.8m</td>
</tr>
<tr>
<td>Overdrive</td>
<td>25m</td>
</tr>
<tr>
<td>BE to CT</td>
<td>20m</td>
</tr>
<tr>
<td>Cut depth</td>
<td>0.5m</td>
</tr>
<tr>
<td>Cut time</td>
<td>1.617min (86s cutting time+10 s positioning time)</td>
</tr>
<tr>
<td>Time before cutting</td>
<td>0.5min</td>
</tr>
<tr>
<td>Time after cutting</td>
<td>0.5min</td>
</tr>
<tr>
<td>Support time</td>
<td>17min/m</td>
</tr>
<tr>
<td>SC discharge time</td>
<td>1.6min (86s + 10s positioning time)</td>
</tr>
<tr>
<td>SC speed</td>
<td>96m/min</td>
</tr>
<tr>
<td>Cut breakaway time</td>
<td>300 minutes</td>
</tr>
</tbody>
</table>

The panel was developed by two CMs, namely CM007 and CM008, each with one SC.

The development task sequences for each miner are as shown in Figure 5.1. The CM007 follows the red arrows in the sequence of 1-2 which is the left part of the panel, while the CM008 follows the blue arrows in the sequence of A-B-C which is the right part of the panel.
Figure 5.1 The task sequences of each CM
5.2. The Shift Schedule and Delays

Delay data, shift schedules and production data were collected from 22/06/2013 to 3/08/2014 (408 days or 58 weeks) for the two production groups of continuous miners. Face operations, such as stone dusting and the panel advance were included in the delay profile.

5.2.1. CM007 Operation Data

- There were 72 days with 24 hours delay in the delay records. Those delays were configured using a shift schedule as per the following:

  - No production on Sundays and 6 hours off on Saturdays

- The rest delays fitted with a Beta distribution with parameters as shown in Figure 5.2, Figure 5.3 and Figure 5.4 are the reports of fitting results and the comparison between delay sample data with the theoretical Beta distribution.
The recorded development achievement during the period is 8039.8m for CM007, which is about 19.7 m/day.
### Relative Evaluation of Candidate Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Relative Score</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Beta</td>
<td>100.00</td>
<td>Lower endpoint</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper endpoint</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #2</td>
</tr>
<tr>
<td>2 - Weibull(E)</td>
<td>92.39</td>
<td>Location</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape</td>
</tr>
<tr>
<td>3 - Johnson SB</td>
<td>92.39</td>
<td>Lower endpoint</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper endpoint</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #2</td>
</tr>
</tbody>
</table>

24 models are defined with scores between 1.09 and 100.00

### Absolute Evaluation of Model 1 - Beta

**Evaluation:** Good

**Suggestion:** Additional evaluations using Comparisons Tab might be informative. See Help for more information.

### Additional Information about Model 1 - Beta

"Error" in the model mean relative to the sample mean = 0.01788 = 0.12%

Figure 5.3 The fitting results report of CM007 delays
5.2.2. CM008 Operation Data

- There were 67 days with 24 hours delay in the delay records. Those delays were configured using shift schedule as per the following:
- No production on Sundays and 3.5 hours off on Saturdays
- The rest delays fitted with a Beta distribution with parameters as shown in Figure 5.5. Figure 5.6 and Figure 5.7 are the reports of fitting results and the comparison between delay sample data with the theoretical Beta distribution.
Figure 5.5 The delay input of CM008

<table>
<thead>
<tr>
<th>Model</th>
<th>Relative Score</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Beta</td>
<td>98.00</td>
<td>Lower endpoint: 0.420267</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper endpoint: 33.859399</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #1: 6.888664</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #2: 9.24046</td>
</tr>
<tr>
<td>2 - Johnson SB</td>
<td>97.00</td>
<td>Lower endpoint: 0.06133</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper endpoint: 33.21055</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #1: 0.48008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape #2: 1.92406</td>
</tr>
<tr>
<td>3 - Weibull(E)</td>
<td>93.00</td>
<td>Location: 3.52690</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scale: 12.50673</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape: 3.06850</td>
</tr>
</tbody>
</table>

25 models are defined with scores between 0.00 and 98.00

Figure 5.6 The fitting results report of CM008 delay sample data
Figure 5.7 The comparison between CM008 delay sample data and the Beta distribution

- The recorded roadway development achieved during the period is 8029.8m for CM008, which is about 19.7m/day. However, as shown in Figure 5.1, CM007 was scheduled at 32.8m, roughly 25% more development than that scheduled for CM008 in the pillar as shown in Figure 5.1, which means the development rates of the two CMs should also be different by about 25%. It was impossible for the CMs to achieve similar development advance with such task sequences as in Figure 5.1. It is possible that the actual task sequences in the recorded period were different from the standard plan, which should be identical or at least close. In order to simulate and get a result with close development rates for both CMs, the task sequences of each CM should be also close.
5.3. The Simulation Results

The planned task sequences shown in Figure 5.1 were configured and simulated for 10 pillars with the development tasks assigned to each CM according to the standard plan; then another modified task sequences model which the two CMs have the same length of development tasks, was also simulated and discussed.

5.3.1. Model validation

Figure 5.8 shows the summary of the simulation results. Specifically, the development rate of CM007 (CM1 in the model) was 20.6m, while CM008 was 16.8m. This further confirmed the comments on page 85. In order to ensure the same development rate for both CMs, the development task should be assigned equally with identical target lengths of roadways to develop.

![Summary](image.png)

Figure 5.8 The summary of the simulation results with planned task sequences

Figure 5.9 shows the simulated results using modified task sequences. In this model, both CM007 and CM008 were assigned 33.2m of the cut-through and 125m of heading
roadway. From Figure 5.9, both CMs achieved 19.7m of development rate, which is the same as the recorded historical production rate.

![Table and diagram]

Figure 5.9 The summary of the simulation results with modified task sequences

Figure 5.10 is the simulated utilization of the CM with modified task sequences. The figure shows that only 4.4% of the calendar time was utilized for cutting, while about 60% of the calendar time was wasted due to varies delays. Also, the CM spent 9.1% of the cutting time waiting for the SC, and about three times (13%) of the cutting time on the support operation. It means that, the SC and the support operation were the possible bottlenecks impacting on the operation time.
The utilization of the CM

5.3.2. The coal transportation

A sensitivity analysis has been done to further study the influence of the shuttle, the support operation and the delay time which are the key elements of roadway development. Figure 5.11 shows the development rate versus a range of support times from 6 minutes to 24 minutes for three cases.

- Case 1: SC speed was set at 96 m/minutes while the discharge time was set to be 1.6 minutes; all other settings remained unchanged.
- Case 2: SC speed was set at 106 m/minutes while the discharge time was set to be 1.2 minutes; all other settings remained unchanged.
- Case 3: the delay profile was multiplied by 80% with all other settings remained the same as of Case 2.
Figure 5.11 The development rate versus support time of the three cases

As shown in Figure 5.11, the performances fluctuated due to the randomness of the breakdowns. Case 2 didn’t always demonstrate better performance with faster coal transportation and discharge. With the support operation time being more than about 16 minutes per metre, fast tramming and quick discharge of the SC didn’t contribute to the overall development rate of the panel, when the support operation was the major constraint. When the support operation gradually became less of a constraint, a fast SC could improve the development rate by up to 10%. The conclusion can be also made that the development rates were very sensitive to the support operation time, which has a roughly linear relationship between the support operation time and the development rate. When the support operation time ranged from 6 minutes to 24 minutes per metre, the development rate could be halved from about 28 m/day to about 14 m/day. The site support operation practice was about 17 minutes per metre, if the support operation can
be improved to be within 12 minutes per metre, the overall performance would be improved by 20%, from about 20m a day to 24m a day. If the 12 minutes per metre support operation could be achieved, the performance can be further improved by another 10%, from about 24m a day to more than 26m a day by utilizing a faster SC for the coal logistics. A 12-minutes-per-metre-support operation is actually achievable using today’s technology and management. What’s more, fast support operations were noticed in the historical data in some cycles in the actual operations, which means, the performance had the potential to be increased by 30% with current technology and faster coal transportation.

5.3.3. The supply of support materials

The base model of miner supply was set to be 30 minutes for every 25m heading advancement. The total miner supply time is about 1.6% of the total calendar time. In order to study the influence of the materials supply on the roadway development rate, this study has been set to simulate the operation by changing both the frequency of the supply and the duration of the supply. The frequency was set to a series of intervals, 15m, 20m, 25m, 30m, 35m and 40m; while the duration was set to range from 10 minutes to 40 minutes. However, due to the total duration of material supply being a small proportion of the whole operation, the simulated results have less than one percent random change with fluctuation. In other words, the randomness of the breakdowns has more influence than the change of the miner supply operation.
Thus, the simulation and analysis of miner supply was improved by studying purely roadway development operations, which are cutting, loading, supporting, miner supply, extending ventilation tubes, cut breakaway and stone dusting. The idea was to simplify the process as much as possible in order to better understand the influence of the material supply to the development panel. The base model was set with the following parameters without panel advance delay, breakdowns and shift schedules:

- pillar size: 125 m x 71.8 m (66.6m centre to centre)
- overdrive: 25m
- BE to CT: 20m
- cut depth: 0.5m
- cut time: 1.617 min (87s cutting time+10 s positioning time)
- time before cutting: 0.5 min
- time after cutting: 0.5 min
- support time: 17.0 min/m
- SC discharge time: 1.6 min (86 s +10 s positioning time)
- SC speed: 96 m/min
- cut breakaway time: 300 minutes
- extend vent tube: 2 minutes every 4m
- stone dusting: 60 minutes every 50m or every 24 hours which comes first
- miner supply: 30 minutes every 25m
The simulated results are shown in Figure 5.12. As can be seen from Figure 5.12, the duration of material supply has a linear relationship with the roadway development rate across all supply intervals. Specifically, the slope ratio increases if materials supply is more frequent. However, with four times the duration change, the development rate only changes from about 3.33% at the least frequent supply to about 8.33% at the most frequent supply, which means the material supplement duration only has a minor influence on the roadway development rate.

The effects of miner supply on development rate

Previous analysis in Sections 5.3.1 and 5.3.2 was based on fixed time duration. The actual miner supply time changes dynamically due to the distance change from the miner to the material storage location as the panel extends. Thus, a further study was done to study the effects of the distance from the material storage location to the miner on the roadway development rate. The following assumptions were made:
• the materials were transported by a LHD with a travel speed of 80 m/minute both loaded and empty;
• the total time to load the LHD and discharge materials from the LHD is 10 minutes fixed;
• the miner stops when material supply is called and when the LHD starts to load, the miner resumes work when the LHD leaves the panel working zone;
• the frequency of the material supply is at 25m intervals.
• the two continuous miners are supplied by two LHDs without interference;
• the distance is measured from the last cut through of the tail heading to the material storage location. Therefore, the distance from CM007 is 66.6m longer than that from CM008. In this study, the distances were set to range from 50m to 550m at an interval of 100m.

The simulated results are as shown in Figure 5.13.

![The effect of the material storage distance on development rate](image)

Figure 5.13 The effect of the material storage distance on the development rate
As can be seen from the Figure 5.13, the material storage distance basically has a linear relationship with the roadway development rate. However, the effect is minor, where the change is only 0.7m per day (1%) with about 500 metre difference of the total distance. For every 100m decrease in distance between the material storage and the development heading, it only makes about a 0.2% improvement in the development rate.

From the simulation and analysis of material supply to the roadway development headings, the conclusion can be made that, the material supply only has a minor effect on the roadway development rate, with respect to the duration, frequency of the material supply operation and the distance to the material storage. However, as observed at the actual practice, logistics does have a noticeable effect on the performance. As can be seen from the simulation, such effect does not come from the material supply of the development panel, nor the operation, the equipment, or the location of the material storage. Therefore, the actual logistics effect may come from other parts of the operation, such as the communication and scheduling of the material supply from the surface of the mine to the panel material storage spot or machine breakdowns, which usually causes a long-time delay.
5.3.4. The effect of downtime and scheduling delay of material supply on the development

Based on the analysis above, long delay outside the development face might be the major cause of the material supply constraint, other than the working face supply which has a minor effect. A further study was done by integrating random and scheduled long downtime to the material supply process using the base model of 10 minutes fixed delay plus travel delay when the materials are stored 50m away. Assumptions were made as following:

- Case 1: uniformly distributed delays from 2 hours to 4 hours and 3 hours to 6 hours for every 40m developed which means about four times of delay per continuous miner per pillar;
- Case 2: uniformly distributed delays from 2 hours to 4 hours and 3 hours to 6 hours happens randomly every 8 hours to 16 hours which means a delay per every one to two shifts (about every 3-5 shifts with actual breakdowns and scheduled down time which is about 60% -65% of total calendar time);
- Case 3: integrating delays of both Case 1 and Case 2.

The simulation results are as shown in Figure 5.14. As can be seen from the figure, the integrated delays have a very large effect on the roadway development rate. An average of two hours delay for every 40m advancement can cut down the total development rate by 15%, while 22% development rate drop would be caused by an average of two hours
delay at the frequency of about every 12 hours on average. The effect of both type of delays brought in a 39% drop of the development rate when compared with the base model. With a one-hour incremental delay applied to both types of delay a 51% decrease in the development rate was simulated. Similarly, an average of three hours delay for every 40m advancement can cut down the total development rate by 20%, while 33% development rate drop would be caused by an average of three hours delay at the frequency of about every 12 hours on average. The simulation results supported the opinion that the random long-time delay of logistics causes the major problem of logistics which may come from the communication and scheduling of the material supply from the mine surface to the panel material storage spot or the machine breakdown.

Figure 5.14 The effect of downtime and scheduling delay of material supply
5.4. Summary on the simulation experiments

The simulation results were compared with performance data collected from mine site. The two major parts of logistics in the roadway development were coal transportation out of the working face and material supply to the working face. The results showed that the major logistics problem was not caused by either coal transportation from or material supply to the working face when the operation is support constrained. More specifically, if the support operation can be improved to 12 minutes per metre from current support operation time at 17 minutes per metre, the overall performance would be improved by 20%, i.e. at from about 20m a day to 24m a day. If the 12 minutes per metre support operation could be achieved, the performance can be further improved by another 10%, from about 24m a day to more than 26m a day by utilizing a faster SC for the coal transport logistics.
6. SUMMARY AND CONCLUSION

A validated underground coal mining FLEXIM model focusing on roadway development and relevant logistical systems has been developed and utilized for this thesis. The model can be used to analysis production performance, capacity bottlenecks and equipment utilization to determine production rates for the purpose of planning, forecasting or identifying improvement activities associated with roadway development. It allows engineers, mine operators and researchers to optimize the selection of equipment and other resources by evaluating alternative “what if” scenarios via the model, rather than during costly and time-consuming field trials. In this thesis, a simulation model was used to study the roadway performance under different logistics options, support operation times, delay profiles. The study showed that:

1. When the support operation time is reduced, there is an increase in the roadway development rate.
2. Higher SC speed improves roadway development advance rate.
3. Roadway development rate can be improved by moving the material storage areas close the face.

The 3D discrete event simulation model surpasses other methods such as spreadsheet analysis by incorporating two key parameters: analysis over a period of time and statistically varied random and non-random events, such as random breakdowns and planned maintenances, to incorporate real-world interferences and delays into the model. The 3D animation of the model allows engineers and mine operators to view the
dynamic production system as it operates, resulting in a far better understanding of the actual production system operation.

By the utilization of both historical data and assumed parameter setups of the two-heading roadway development operation, the case studies fully examined the logistics of both coal transportation from the continuous miner out bye and the material supply to the development headings in bye.

The roadway development rate is affected by multiple factors. The simulation and analysis of coal transportation together with support operations showed potential for a 30% performance increase with current support technology and faster coal transportation. As for the material supply to the development face, the material supply only has a minor effect on the roadway development rate, regardless of either the duration or frequency of the material supply operation, or the distance from the material storage. Furthermore, the simulation results and analysis support the argument that random long-time delays associated with logistical supply cause major logistical issues which may come from either the communication and scheduling of material supply from outside the mine to the panel material storage area or the breakdown of machines.
7. MODEL LIMITATION AND FUTURE WORK

Even through this study has demonstrated the successful utilization of a 3D discrete event simulation replicating underground roadway development in a coal mine, it also highlighted some limitations that need to be improved in future work.

Underground coal mining is a complex process that occurs within a limited space. Even a small incident can affect the whole process. Incidents may include the stoppage of a belt conveyor or the ventilation system, dust and gas hazards, heat hazards, water hazards, geometrical conditions, the injury of a miner or even the blockage of the road. These factors might have different ways of influencing production performance with a sub-set of parameters. Take material supply for example, scheduling, the travel speed in different zones, the capacity, the type of material, loading and discharge speed, the interaction between the cars and the route travelled all have an impact on supply. However, in this model, only subsets of factors were considered in the model logic. As for the logistics module, the limitations include the following:

- no interactions between the transports, for example, they don’t give way to each other;
- the scheduling frequency of the transports has been set to be at full capacity which makes mining labour and material always available, even though there was logic to stop the operations when there is insufficient labour or material.
- the lack of real scheduling data.
Therefore, the model needs more work to include more factors in detail so as to replicate as near as possible the onsite operation.

Another major limitation of this study was the historical data and production performance KPIs. This study only studied one development panel operating in a certain period of time with only one KPI being the development rate in metres/day due to the time frame limitation of this research. Future work can be progressed using more case studies in different production panels and different mines with different production time frames and focusing on more KPIs.
8. REFERENCES

ANANI, A. 2016. Applications of simulation and optimization techniques in optimizing room and pillar mining systems. PhD Thesis. Missouri University of Science and Technology, US.


IMPACT MINING, 2017. [Online]. Available:
[Accessed 23.03.2017].

JOY GLOBAL, 2017a, [Online]. Available:

JOY GLOBAL, 2017b. [Online]. Available:


[Accessed 12.05.2017].


MACQUARIE MANUFACTURING, 2017.


MINING GLOBAL. 2017. [Online]. Available:


MSEC. 2017. Introduction to Longwall Mining and Subsidence. [Online]. Available:


9. APPENDICES

9.1. APPENDICE A - the program script of the new designed roadway object

/**draw pillars Code*/

treenode current = ownerobject(c);

treenode view = parnode(1);

// If this function returns a true, the default draw code of the object will not be executed.

int pillarnodenum=content(labels(current)); //number of pillar groups

drawtomodelscale(current);

fglDisable(2884);

double prelength=0; //for preview SC routh

for (int k=1; k<=pillarnodenum; k++) //draw shape of all pillar groups
{

treenode curpillargroup=rank(labels(current),k); // one pillar group

int cmnum=getnodenum(node("/cm1",curpillargroup));

treenode datanode2=rank(labels(current),k-1);

if (objectexists(datanode2))
{ 
	treenode pillardata2=first(datanode2);

prelength += getnodenum(node("/other/2/pillarlength",datanode2))*getnodenum(node("/cm1/pillar",datanode2));
}

for (int l=1;l<=cmnum;l++)
{

treenode icm=rank(curpillargroup,l+1);

treenode pillardata=first(icm);// pillar data

int pillarnum=0;//number of pillars

int sectionnum=0;//number of sections

double pillarlength=getnodenum(node("/other/2/pillarlength",curpillargroup));

int numpreviewpillar=getnodenum(node("/other/preview/1",curpillargroup));

if ( numpreviewpillar) // preview

	pillarnum=getnodenum(pillardata);

else

	pillarnum=getnodenum(node("/current/curpillar",rank(curpillargroup,2)));
for (int i=1; i<=pillarnum; i++)
{
if (i < pillarnum || getnodenum(node("/current",icm)))
    sectionnum=content(pillardata);
else
    sectionnum=getnodenum(node("/current/cursection",icm));

if (numpreviewpillar) // preview
    sectionnum=content(pillardata);

for (int j=1; j<=sectionnum; j++) // draw shape
{
    treenode cursection=rank(pillardata,j);
    treenode colornode=node("/color",cursection);
    double cR=getnodenum(rank(colornode,1));
    double cG=getnodenum(rank(colornode,2));
    double cB=getnodenum(rank(colornode,3));
double colorR=cR*255;

double colorG=cG*255;

double colorB=cB*255;

double opacity=getnodenum(rank(colornode,4));

double length=0; //////////////

if ( i==pillarnum && j == sectionnum && !getnodenum(node("/current",icm))) //current section of current pillar

    length=getnodenum(node("/current/curlength",icm));

else

    length=getnodenum(node("/sectionsize/length",cursection));

if ( numpreviewpillar) // preview

    length=getnodenum(node("/sectionsize/length",cursection));

double height=getnodenum(node("/sectionsize/height",cursection));

double width=getnodenum(node("/sectionsize/width",cursection));

double halfwidth=width/2;

double
locstartx=getnodenum(node("/locstart/1",cursection))+pillarlength*(i-1)+prelength;

double locstarty=getnodenum(node("/locstart/2",cursection));
double locstartz=getnodenum(node("/locstart/3",cursection));

double roty=getnodenum(node("/rotation/3",cursection)); //OpenGL y = Flexsim z

double rotin=getnodenum(node("/rotation/2",cursection));

double rotout=getnodenum(node("/rotation/1",cursection));

double headingnum=getnodenum(cursection);

if (round(frac(headingnum),1)==0.1)
{
    length = -length;

    roty = 180-roty;
}

double rotyrad=degreestoradians(roty);

double rotinrad=degreestoradians(rotin);

double rotoutrad=degreestoradians(rotout);

double sinry=sin(rotyrad);

double cosry=cos(rotyrad);
\texttt{double tanrin=} \texttt{tan(rotinrad);} \\
\texttt{double tanrout=} \texttt{tan(rotoutrad);} \\
\texttt{double hwsinr=} \texttt{halfwidth*sinry;} \\
\texttt{double hwtanrin=} \texttt{halfwidth*tanrin;} \\
\texttt{double hwtanrinsinr=} \texttt{hwtanrin*sinry;} \\
\texttt{double hwtanrincosr=} \texttt{hwtanrin*cosry;} \\
\texttt{double hwtanrout=} \texttt{halfwidth*tanrout;} \\
\texttt{double hwtanroutsinr=} \texttt{hwtanrout*sinry;} \\
\texttt{double hwtanroutcosr=} \texttt{hwtanrout*cosry;} \\
\texttt{double hwcosr=} \texttt{halfwidth*cosry;} \\
\texttt{double middleendx=} \texttt{locstartx+length*cosry;} \\
\texttt{double middleendy=} \texttt{locstarty+length*sinry;} \\
\texttt{double x1=} \texttt{locstartx-hwsinry-hwtanrincosry; \textit{// dot1 and dot3}} \\
\texttt{double y1=} \texttt{locstarty+hwcosry-hwtanrinsinr;} \\
\texttt{double x7=} \texttt{locstartx+hwsinry+hwtanrincosry; \textit{// dot5 and dot7}}
\textbf{double} \quad y7=locstarty-hwcosry-hwtanrinsinry;

\textbf{double} \quad x2=middleendx-hwsinry-hwtanroutcosry;

\textbf{double} \quad y2=middleendy+hwcosry-hwtanroutsinry;

\textbf{double} \quad x8=middleendx+hwsinry+hwtanroutcosry;

\textbf{double} \quad y8=middleendy-hwcosry-hwtanroutsinry;

drawtomainmodelscale(current);

\textbf{int} \quad itemselscct=getnodenum(node("\texttt{highlighted}",current));

\textbf{if} \quad (k==itemselscct \land \ getnodenum(up(current))//up(current)==1, \text{ when in the setup view})

\{

\begin{verbatim}
opacity=1;
\end{verbatim}

//locstartz+=5;

\textbf{int} \quad cmselscct=getnodenum(node("\texttt{highlightedcm}",current));

\textbf{int} \quad sectionselscct=getnodenum(node("\texttt{highlightedsection}",current));

\textbf{if} \quad (1==cmselscct \land \ j==sectionselscct)

\begin{verbatim}
locstartz+=height/2;
\end{verbatim}
if (getnodenum(node("/other/preview/3", curpillargroup)))
{

double textroty = -roty;

if (round(frac(headingnum), 1) == 0.1)
{

textroty = 180 - roty;

}

drawtext(view, concat("Seq.", numtostring(j), " of ", getname(icm)), x1, -y1, height*1.4, 15, height*0.2, 90, 0, textroty);
}

glBegin(GL_QUAD_STRIP);

fglColor(cR, cG, cB, opacity);

glVertex3d(x1, locstartz, y1); // dot 1

glVertex3d(x2, locstartz, y2); // dot 2
glVertex3d(x1, locstartz+height, y1); // dot 3

glVertex3d(x2, locstartz+height, y2); // dot 4

glVertex3d(x7, locstartz+height, y7); // dot 5

.glVertex3d(x8, locstartz+height, y8); // dot 6

.glVertex3d(x7, locstartz, y7); // dot 7

.glVertex3d(x8, locstartz, y8); // dot 8

.glVertex3d(x1, locstartz, y1); // dot 1

.glVertex3d(x2, locstartz, y2); // dot 2

.glEnd();

} 

} 

}

} 

}

}

}

.glLineWidth(3);

if (getnodenum(node("/other/preview/2", curpillargroup))) // preview SC travel route

{


treenode routedata=node("/other/length",curpillargroup);

int SCrouteselsct=getnodenum(node(">highlightedSCsection",current));

for (int m =1; m<=content(routedata); m++)
{
    int itemselsct=getnodenum(node(">highlighted",current));
    double highlightz=3;
    double highlightz2=5;
    int linecolorR=1;
    int linecolorG=0;
    if (!(m-SCrouteselsct) && !(k-itemselsct) && getnodenum(up(current))) // highlight the selected route section in the setup view
    {
        linecolorR=0;
        linecolorG=1;
    }
    treenode heading=rank(routedata,m);
    double headingnum=stringtonum(getnodename(heading));
if (!frac(headingnum)) //heading
{
    for (int n = 1; n <= content(heading); n++)
    {
        treenode routesection = rank(heading, n);
        double
fromx = getnodenum(node("/from/x", routesection)) + prelength;
        double fromy = -getnodenum(node("/from/y", routesection));
        double tox = getnodenum(node("/to/x", routesection)) + prelength;
        doubletoy = -getnodenum(node("/to/y", routesection));

//gILineWidth(3);
        drawcylinder(fromx, fromy, highlightz, 0.5, 3, 0, 0, 0, 0, 255);
        drawline(view, fromx, fromy, highlightz2, tox, toy, highlightz2, linecolorR, linecolorG, 0);
        drawcylinder(tox, toy, 2, 0.5, 0, highlightz, 0, 0, 0, 0, 255);
else  //cut through
{

for (int n =1; n<=content(heading); n++) 
{

for (int j=1; j<=2; j++)
{

treenode routesection=rank(heading,n);

double fromx=getnodenum(node("/from/x",routesection))+prelength;

double fromy=-getnodenum(node("/from/y",routesection));

double tox=getnodenum(node("/to/x",routesection))+prelength;

double toy=-getnodenum(node("/to/y",routesection));

drawline(view, fromx,fromy,highlightz2, tox,toy,highlightz2, linecolorR,linecolorG,0);
9.2. APPENDICE B - Modules or variables that affect the development