

School of Mining Engineering



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JOHANNESBURG

**A SYSTEMS THINKING APPROACH TO OPERATING
A COAL MINE: A CASE STUDY OF THROUGHPUT
AND VALUE CHAIN INTEGRATION AT ARNOT COAL
MINE.**

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DECLARATION

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ABSTRACT

Arnot Coal Mine is a case study for applying systems thinking methodology for managing a complex environment. The Arnot Coal Mine aimed to meet planned production targets at a minimal cost within a specific period. The mine's production decreased from 2004 until the mine closure. Variable throughput and product qualities led to the mine failing to operate at its potential capacity. This study explored qualitative and quantitative research techniques. The research was based on the systems thinking theory (encompassing the complexity theory) and the Mineral Resource Throughput Management principles. Systems thinking recognises and identifies interconnections, non-linear behaviour, feedback, and dynamic behaviour. Systems thinking is revealed in holism rather than in disintegrated parts. Mineral Resource Throughput Management integrates variability in physical operating conditions, characteristics of the plant process, and the ore's attributes into the decision-making process and business logic. The study findings confirm that the variability inherent in the geology dictates the throughput and the effectiveness of the processes downstream. The ultimate income-generating product is determined by the run of mine quantity and quality as well as interdependent variables and processes. Mining is a non-linear process requiring the recognition of system structure, variables, and the flow (material, information, and synergy) within the entire system. The research aims to understand the operational environment prior to mine closure rather than analysing separate events within individual departments. Therefore, a greater understanding of the value chain allows organisations to understand performance and unlock more potential of the entire system, rather than organisational silos independently. It is,

therefore, recommended that feedback loops, emergent properties, system flow, and system behaviour evaluation be significant in continuous improvement and business decision-making. The three dimensions of Mineral Resource Throughput Management should be accounted for by synchronising the physical material flow, logical decision-making, and product payability.

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LIST OF ABBREVIATIONS

ACM	Arnot Coal Mine
AI	abrasive index
BBBEE	Broad-Based Black Economic Empowerment
BPM	Business Process Management
BPR	Business Process Redesign
CCR	capacity-constrained resource
CM	continuous miner
CPA	critical performance area
CSA	Coal Supply Agreement
CV	calorific value
DMS	dense medium separation
EBITDA	earnings before interest, taxes, depreciation, and amortization
KPI	key performance indicators
Ktpa	kilo tonnes per annum
LOM	life-of-mine

MQA	Mining Qualifications Authority
MRM	Multiple reaction monitoring
MRTM	Mineral Resource Throughput Management
Mt	million tonnes
Mtpa	million tonnes per annum
NASA	National Aeronautics and Space Administration
RD	relative density
ROM	run-of-mine
RPEEE	Reasonable Prospect for Eventual Economic Extraction
S1	Seam 1
S2L	Seam 2 Lower
SAMREC	South African Mineral Resource Committee
SANS	South African National Standards
STA	Systems thinking approach
T	tonnes
TOC	theory of constraints

TS	total sulphur
VM	volatile matter

1 INTRODUCTION AND BACKGROUND OF THE STUDY

1.1 Introduction

This chapter builds the study foundation by presenting the background of the problem statement, interrogated in subsequent chapters. The Arnot Coal Mine (ACM) experienced decreasing production and increasing costs until mine closure. Over the years, ACM had significant throughput and variable product qualities that did not meet required specification. The justification for this research is outlined in the research methods.

1.2 Background

The Arnot Coal Mine (ACM), transferred under the new ownership and management of Arnot OpCo (Pty) Ltd in 2019, went under care and maintenance in 2015. Arnot OpCo is a junior miner, officially taken over the mine in 2020. Junior coal mining companies are increasing in the coal mining industry in South Africa. Ncube (2020) remarks that junior mining companies account for 30% of South African coal production. According to the Mineral Council of South Africa, Junior mining is defined as companies with a gross asset value between R18 million and R8 billion (Ncube, 2020). The divestment of major mining companies, such as Exxaro, Anglo-American, and South32 from coal operations allowed junior miners to participate in the industry.

ACM is a new entrant in the coal mining industry. The mine went into care and maintenance in 2015 under the ownership of Exxaro, owing to the lapse of the Eskom Coal Supply Agreement (CSA). The company acquired the ACM as a

Broad-Based Black Economic Empowerment (BBBEE) transaction from Exxaro in 2020.

1.3 Arnot Coal Mine

The Arnot Coal Mine (ACM) is in Mpumalanga, South Africa (Figure 1). The mine covers an area of 14 997 hectares. ACM is in the Witbank Coalfield, the northern part of Main Karoo Basin. The mine is on the eastern side of the Witbank Coalfield.

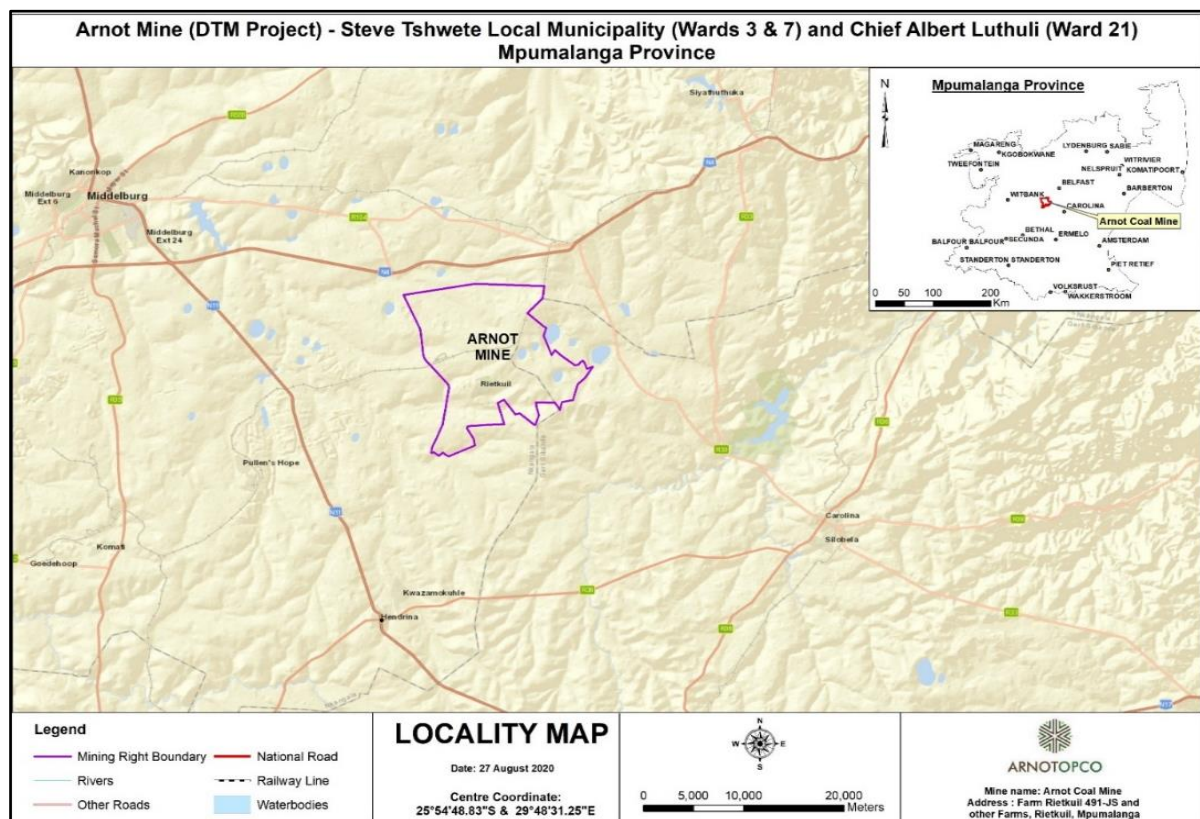


Figure 1. A locality map for Arnot Coal Mine (Arnot OpCo, 2020).

The stratigraphy of the mine contains the five classical Witbank Coalfield seams (Seam 5, Seam 4, Seam 3, Seam 2, and Seam 1); however, the stratigraphic column of the mine is reduced to 80m. Seam 2 Lower (S2L) and Seam 1 (S1) are the only economical coal seams. S2L is well developed in the underground and opencast reserve areas, whereas S1 is mined only in the opencast reserve areas.

In 2020, the total resources and reserves were 153.9 Mt and 48.9 Mt, respectively (Arnot OpCo, 2020). Underground and opencast mining methods were used to extract coal from the mine. The S2L coal seam was extracted from two underground shafts, No. 8 Shaft and No. 10 Shaft, using mechanised mining equipment through board and pillar extraction mining methods. The opencast areas extracted the S2L and S1 coal using truck and shovel. Opencast mining ceased in 2011, and underground mining ceased in 2015.

The maximum throughput the mine produced was 6.4 Mtpa in 2004. Throughput steadily decreased over the years (from 2004 to 2015) to a throughput of 1.4 Mtpa in 2015. Run-of-mine (ROM) coal from underground was conveyed to the crush and screen module of the coal processing plant and conveyed to Eskom's Arnot Power Station stockpile yard.

1.4 Junior Miners Navigating Complex Mining Environments

Several mining operations face complex operational challenges, adopting a reductionist approach, where the system is divided into simple parts to find solutions. Conversely, mining operations encounter challenges requiring a deeper understanding of the interrelationship and network between the parts,

departments, and information flow within the mining value chain. This applies to most operations, with or without technological interventions.

The mining environment's dynamic behaviour causes changing internal and external environments. Junior miners have not escaped the challenges encountered by larger operations; they are more exposed to these challenges. Their survival depends on solving industry-wide difficulties and issues borne by junior miners in South Africa. The mining industry is complex, cyclic, and dynamic. The industry and the coal mining environment evolved since the closure of the ACM. The industry will continue to evolve owing to the increasing pressure for renewable energy, economic uncertainties, and the emergent properties of each operational environment.

According to Ncube (2020), junior miners encounter operational, financial, skilled labour, safety, and equipment challenges. These challenges could hinder their survival in tough economic times. As a result, companies encounter increasing pressure to be more resilient, flexible, and productive to remain competitive (McKinsey & Company, 2020). Junior miners have marginal ore deposits, as the easy to mine deposits with good qualities have been exploited by major companies dominating the coal industry in the past. The benefit is that junior miners have the opportunity to exploit reserves that were less economical for major mining companies.

Mining comprises a complex web of functions and elements, requiring synchronisation for the entire system to operate at its total capacity while creating

sustainable economic value. ACM, as a junior miner, strives to be competitive within the coal mining industry. An integrated, goal-driven system is, therefore, critical for effective strategic and tactical decision-making. Like any other mining operation, ACM had operational challenges highly affecting the throughput, coal qualities, and costs over the years.

1.5 Problem Definition

The mine's production decreased over time until closure (Figure 2). The mine did not deliver the correct coal quality (Figure 3) according to the Eskom specification. Variable throughput and product qualities resulted in the mine failing to operate at its potential capacity. The compounding system variability resulted in increasing working costs, decreasing production, and product qualities below the market specifications. The mine's operation followed the traditional silo approach, lacking a flow-based integration at various levels of the organisation to manage the system's variability and performance.

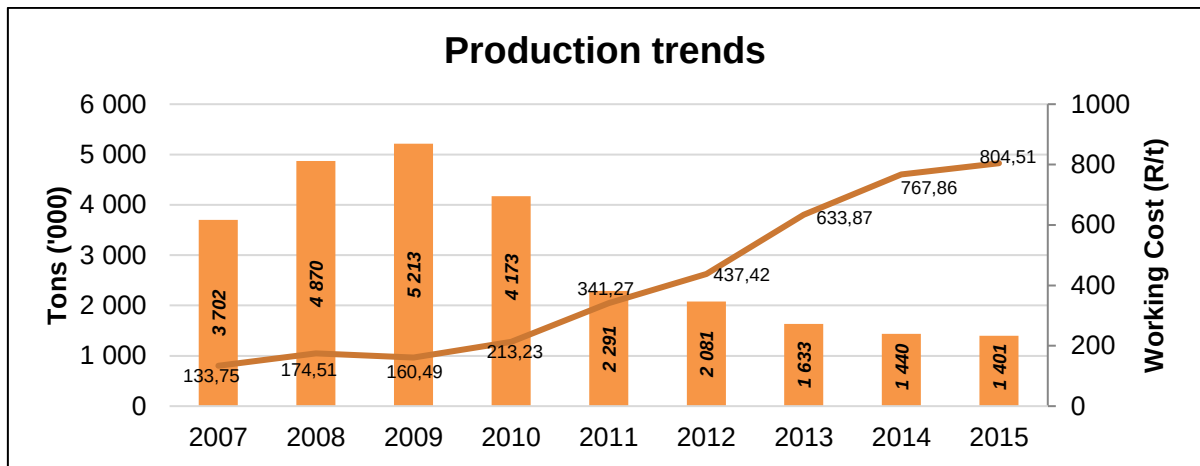


Figure 2. Average production trends from 2007 until mine closure.

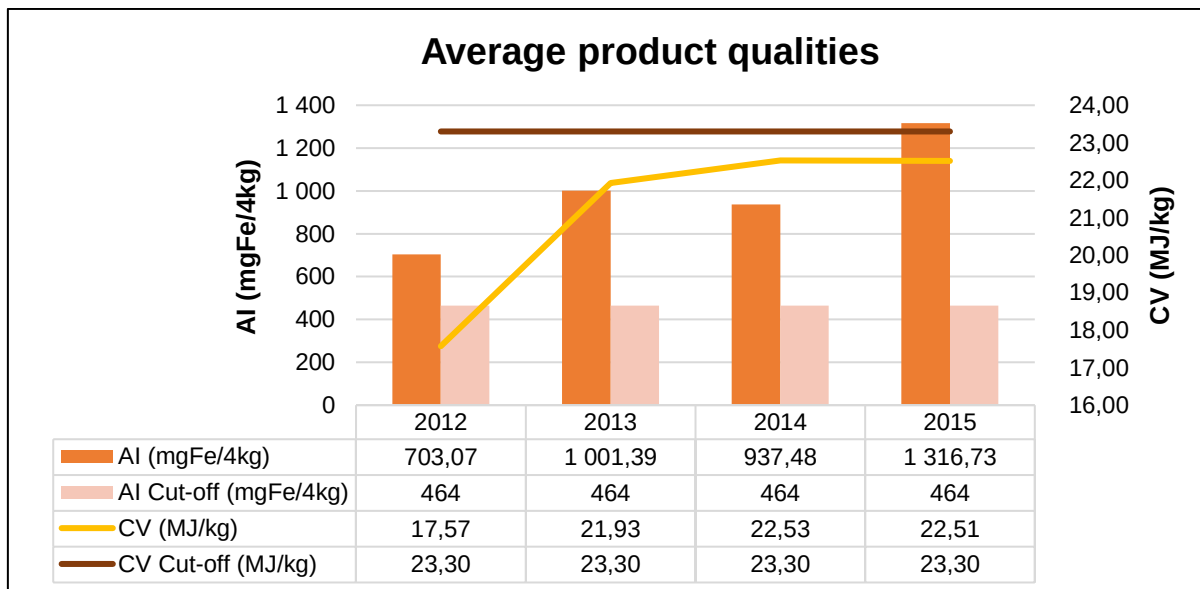


Figure 3. Average product qualities and cut-off limits.

1.6 Justification for Research

Mining is a system of systems, containing interrelated and complex subsystems. The fundamental principles of systems thinking in mining are inadequately adopted in their entirety. This is clear in operations with partial synchronisation, adopting a deterministic approach where problems and tasks relating to the system are divided into simple parts (following a reductionist approach to problem-solving). The visibility of the holistic mining system is usually fragmented along departmental boundaries (Claassen, 2015). Mining in its entirety comprises interconnected elements with various characteristics and behaviours functioning to achieve a defined and measurable goal within its system boundaries.

A holistic systems approach has the potential to yield significant financial benefits. It has proven successful in complex fields of engineering and science, such as the National Aeronautics and Space Administration (NASA), human psychology, environmental ecosystems, education, software development, and manufacturing (Leveson, 2011). Understanding the capacity-constrained resources (CCR), the flow in the system, and the variability's influence is critical to effectively designing and managing the system to maximise its performance (Lane, 2018).

Effective management of the mineral resource and throughput using a systems thinking approach (STA) can create sustainable economic value for all stakeholders. This is fundamental for junior miners as it creates an opportunity for organic growth and competitive advantage by reducing costs, increasing throughput, and managing system flow. This approach can be replicated in all the

subsystems supporting the core function of the entire system, such as safety, human resource management, supply chain, and cost management.

ACM as a junior miner, could reap the benefits of understanding its system's structure and behaviour (archetypes) from embedded feedback loops in the system. This can be achieved by more profound knowledge of how the variables, the critical value drivers, and processes affect throughput behaviour and flow throughout the value chain.

1.7 Research Methods

This research explored qualitative and quantitative research techniques. The study is based on the systems thinking theory, encompassing the complexity theory. These theories contradict the traditional deterministic and mechanical approaches adopted in the mining industry. The STA is considered with the Mineral Resource Throughput Management (MRTM) principles recommended by Claassen and Laurens (2016).

1.8 Structure of the Research Report

1 provides the background while outlining the problem statement. This section emphasises the broader perspective of the mining environment. Mining is a complex system, based on the interdependencies of internal and external factors influencing a mining organisation in its entirety.

Chapters 2 and 3 incorporate the literature review based on the systems thinking and complexity theory. Chapter 2 explores the theories supporting this study and

justifies adopting the proposed methodology for the mining industry. The case study literature where systems thinking benefited operations is explored.

Chapter 3 captures the traditional approach adopted in mining contrasted with the STA to operate a mining system to ensure sustained economic value. MRTM principles are discussed further.

Chapter 4 outlines the methodology. The study employed both quantitative and qualitative methodology techniques. Historical data before mine closure were analysed. The methodology explores systems thinking techniques and MRTM-based flow and integration principles to build a scenario-based model using Microsoft Excel. The Vensim software was used to create causal feedback loops to indicate relationships among variables.

Chapters 5 and 6 present the data and analysis of the historical state of ACM to emphasise inefficiencies in the system. Chapter 6 represents the analysis from a systems thinking perspective. The scenario-based model results are discussed in Chapter 7, while the causal loop diagram of the analysed data is further discussed.

Chapter 8 summarises the results and concludes the study findings. Lastly, Chapter 9 discusses the recommendations for future research following the research findings.

1.9 Conclusion

The introductory chapter provides the mine's background and the problem statement supporting the research. This chapter discusses the challenges junior minors encounter, and the dynamism of the mining environment internally and externally. The research justification is provided by emphasising that effective management of the mineral resource and throughput using an STA can create sustainable economic value for all stakeholders.

The subsequent chapter embraces the systems thinking definition and concept from the literature, considering widely used improvement and management methodologies in mining, adopted from the manufacturing industry.

2 REVIEW OF SYSTEMS THINKING LITERATURE AND JUSTIFYING ITS APPLICATION IN MINING

2.1 Introduction

This chapter presents a literature review, unravelling systems thinking and its constituents. Theories that build up the concept of systems thinking are evaluated; the methodology is motivated and compared to the traditional approach to mining. This chapter contextualises additional improvement and management methods in the industry and their shortcomings in approaching the unique challenges in the mining environment. The proposed method is motivated and supported by projects applying systems thinking and the outcomes of the application from a throughput and safety perspective.

2.2 Systems Thinking Theory

From the literature, the standard and widely accepted notion of systems thinking is that it is interconnected, dynamic, and observed as aggregates rather than fragments (Hopper & Stave, 2007; Senge, 1990; Richmond, 1994). Arnold and Wade (2015) describe systems thinking as “a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them to produce desired effects”. They further urged that systems thinking should:

- Recognise interconnections;
- Identify and understand feedback;
- Recognise system structure;
- Distinguish types of stocks, flows, and variables;
- Recognise and understand non-linear behaviour; and
- Understand dynamic behaviour (Wade & Arnold, 2015).

According to Skyttner (2001), a systems thinking theory and application is observed to overcome the disintegration of knowledge and the segregation of specialists; discover innovative solutions created by earlier resolutions to problems. Systems theorists promote an interdisciplinary science transformed for a universal application using a common language across all disciplines (Skyttner, 2001). Systems thinking is adopted from the context stated by Arnold and Wade (2015) for this study.

The necessity for systems thinking surpasses engineering and science disciplines. Technological advancements may introduce new interconnected subsystems with increasing interdependencies to understand complex behaviours and predict outcomes (Arnold & Wade, 2015). The definition of systems thinking has been evolving since its invention in 1987 by Barry Richmond. According to Arnold and Wade (2015), systems are clusters of interrelated, interdependent, or interacting elements forming collective entities. The basic principle for systems comprises three fundamental aspects, such as

elements or characteristics, interconnections, and a function or purpose (Figure 4) (Arnold & Wade, 2015; Meadows, 2008).

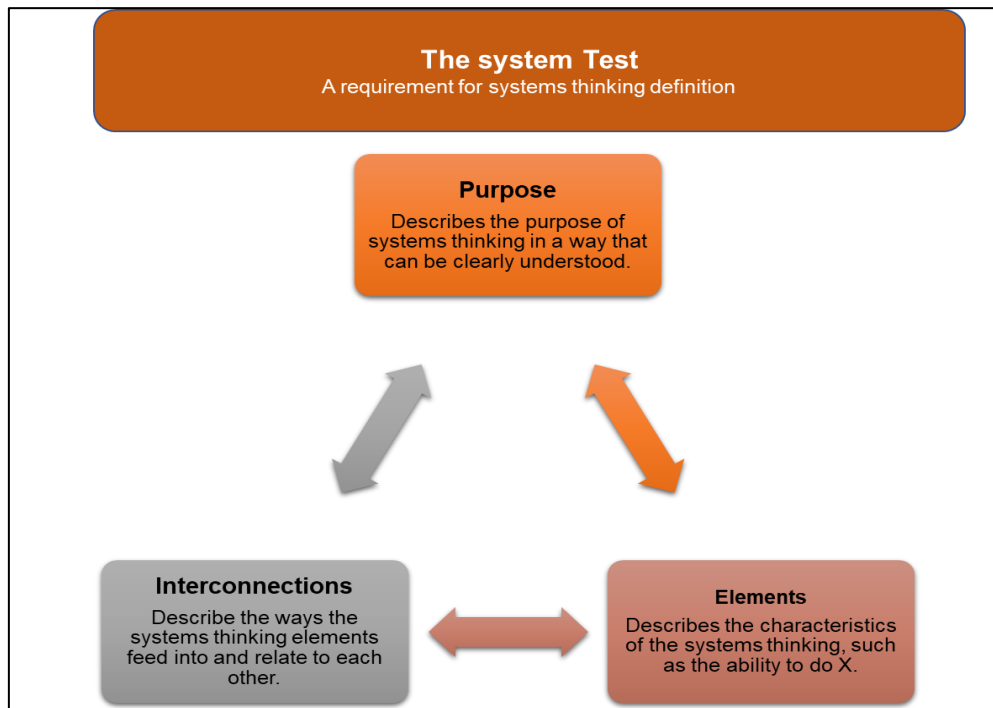


Figure 4. Fundamentals of the definition of a system (Arnold & Wade, 2015).

2.3 The Complexity Theory

The complexity theory is premised on irregularity, disorder, and randomness of the natural systems. It emphasises instability, dynamism, and unpredictability (Jackson, 2003). The theory promotes holism, illustrating that the parts of the system can only be understood concerning their relationships with each other and with the whole (Jackson, 2003). The pattern of relationships determines the system's actions. The theory emphasises that order is an emerging property of disorder, emerging from the self-organising processes within the system

(Jackson, 2003). Complex systems do not adapt to their environment, but they evolve together in response to one another.

2.4 Mechanistic and Organic Systems Theory

Burns and Stalker (1961) describe simple and stable organisations as mechanistic, and complex as organic. Performance is more predictable and is easier to control for simple organisational designs than intricate designs. Mechanistic environments can be managed effectively using the functional approach (silo approach), best practices, and strong hierarchical authority (Claassen, 2016; Burns & Stalker, 1961). The characteristics of a mechanistic organisation include problems and tasks relating to the system divided into simple parts (a reductionist approach).

Conversely, organic organisations (complex environments) are adapted to dynamic conditions, which constantly cause problems and unforeseen actions that cannot be segregated (Burns & Stalker, 1961). A network of control, authority, and communication, and the contribution of special knowledge and experience to the common task characterise this (Burns & Stalker, 1961).

A complex environment, such as mining, cannot use a reductionist approach as it cannot consider complex problems and dynamism. Complex organisations are characterised by non-linear feedback loops resulting in sensitivities towards slight changes in initial conditions (Jackson, 2003).

2.5 Manufacturing Methodologies Widely Adopted in Mining

Improvement and management methodologies commonly adopted in the mining industry for optimisation and value creation have their origin in the manufacturing industry. Claassen (2016) surveyed 22 operating mines to understand the most commonly adopted management and improvement methodologies in the South African mining industry (Figure 5). Most mines employed a hybrid of methods to create and sustain value. The business improvement methods' effectiveness in the mining environment highly depends on applying it in a mechanistic or systemic context (Claassen & Laurens, 2016).

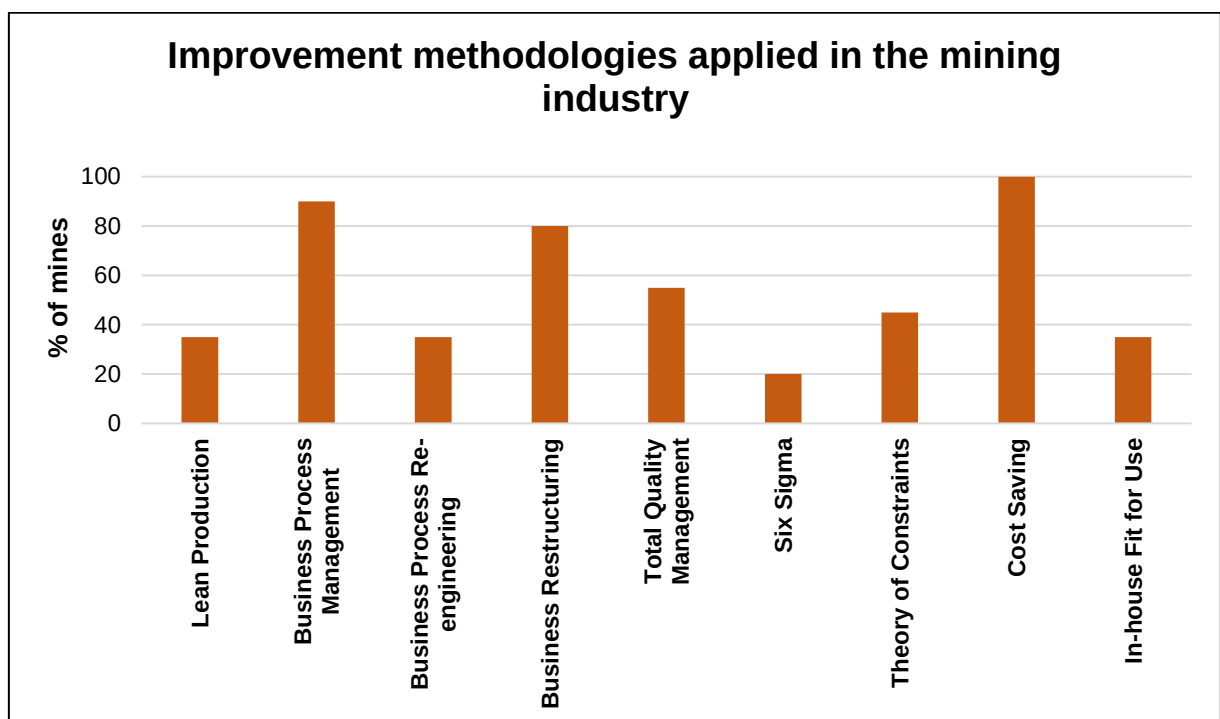


Figure 5: Improvement and management methods applied in the South African mining industry (Claassen, 2016).

All the mines that participated in the survey employed a cost-saving methodology; and, prominently, mines employed Business Process Management and Business Process Redesign (BPR). Thirty-five per cent of the mines adopted in-house fit-for-use methods, illustrating a need for additional effective methods suited for the challenges unique to the mining environment. Mining's unique challenge is to integrate the value chain from geology, mining, and plant subsystems, considering the variability inherent in the raw materials and processes (Lane & Wylie, 2014). The main differences between mining and manufacturing include:

- Variability in the quality of raw materials;
- Variable physical conditions and ore characteristics; and
- Variable mining and plant processes owing to ore characteristics (Claassen, 2016).

2.5.1 Lean production

The method emphasises eliminating waste in the system by focusing on flow, therefore, emphasising the importance of stabilising value chains (Leanproduction, 2021). This method disapproves the optimal integration of geology, mining, and plant subsystem in the value chain.

2.5.2 Business process management and business process re-engineering

BPM strives to improve business processes completely. According to Claassen (2016), process silos are created when this method is applied mechanistically, further creating more dependencies and complexity in the system. BPR requires a radical system redesign focusing on reviewing crucial processes.

2.5.3 Total quality management

This improvement method focuses on optimising each part of the organisation. The focus on individual parts of the system could create cumbersome and expensive business structures, fragmenting the organisation even further (Claassen, 2016).

2.5.4 Six sigma

This method is a set of techniques for process improvement, focusing on eliminating variability by disregarding the defect causes. Variability is inherent in the geology, mining, and plant processes in a mining environment; therefore, variability cannot be eliminated—it must be managed effectively instead (Claassen, 2016).

2.5.5 Theory of constraints

The theory of constraints (TOC) methodology identifies a bottleneck hindering the achievement of the system's goal. TOC assumes complex systems comprising

various activity and process links; one link poses a constraint in the entire system (Leanproduction, 2021). Each process in the system has a constraint, therefore, only when the constraint improves, the total throughput of the system improves. This method supports flow-based improvement and management.

2.6 Traditional Approach to the Management of a Mining System

South African mining companies do not fully embrace an STA to deal with the complexities and uncertainties of mineral asset management for optimal return on investments (McKinsey & Company, 2020). Companies adopted manufacturing and operations management and methodologies to improve the system's performance (Claassen, 2015). Some of these methodologies have shortcomings, such as handling variability, making them less effective in the mining industry (Claassen & Laurens, 2016).

2.6.1 Mine development and mine planning

Traditionally, mining operates in silos with departmental boundaries at various levels of the organisation. The silo approach stems from mineral resource development stages. For example, evaluating mining projects is still executed on present-day value economics only, inadequately integrated to meet the criteria later in the project (Mottola, et al., 2007).

The mine planning process is separate; therefore, disregarding the dynamic behaviour of the mining environment. It uses a deterministic approach while offering static solutions (Graham & Alexandra, 2018; Tholana, et al., 2019).

According to Graham and Alexandra (2018), traditional mine planning yields suboptimal solutions. Mine planning activities, such as resource modelling, mine design and scheduling, resource budgeting, and cost budgeting, are undertaken in fragments (Lane, 2018). Optimised subsystems fail to optimise the entire system. Segments are measured in isolation instead of recognising the relationships among the parts.

2.6.2 Managing the system in silos

The system parts are measured in isolation instead of quantifying, understanding, and measuring the relationships and interdependencies. Often, organisations spend capital on initiatives to improve throughput without understanding the behaviour and variability of the system (Laurens, et al., 2020). Parts of the system are perceived to have linear behaviour. Claassen (2015) remarks that mining personnel usually observe the mining value chain in a functional observation and an activity-based or process observation, as detailed in Figure 6a and 6b.

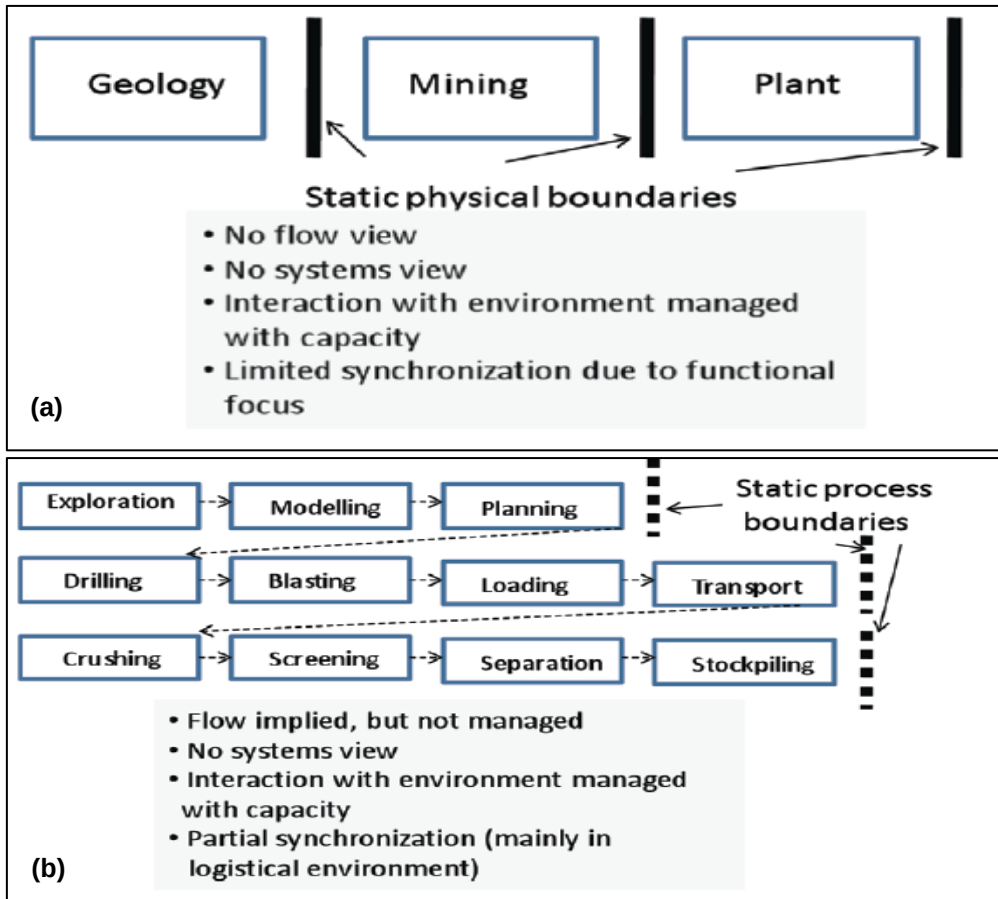


Figure 6. A traditional observation of the mining value chain: (a) a functional and (b) a process observation. (Claassen, 2015).

Figure 6a indicates the functional observation of the mining system characterised by departmental boundaries; no flow and limited integration among the functions were established. Figure 6b demonstrates a process observation, with partial integration between the activities and an inefficiently managed flow. Both approaches lack the observation of a holistic system.

The fragmented observation resulted in a disintegrated method for optimising the parts of the system; therefore, suboptimal system performance was eminent.

Figure 7 demonstrates systems thinking flow observation of a dynamic, integrated system with feedback loops, indicating constraints and interdependencies of activities.

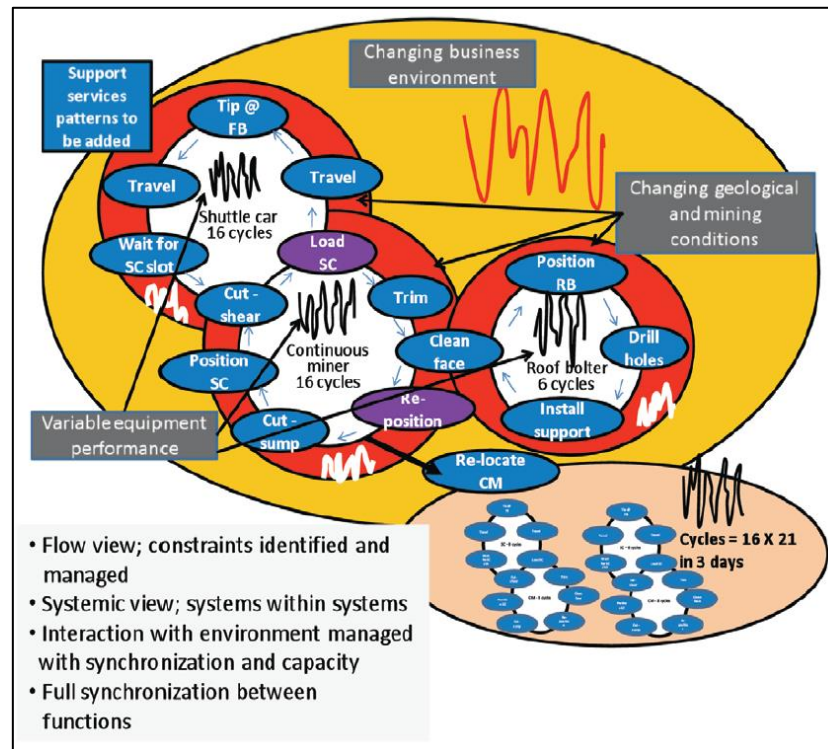


Figure 7. An example of a systems thinking flow observation (Claassen, 2015).

2.6.3 Using average standards in a system characterised by variability

Traditionally, variability constraints were planned, managed, and controlled with average norms and standards. The system is managed in silos, and average standards establish targets for each functional silo and manage the risk of combined interdependencies and variability (Dimmick-Touw, 2019). The central assumption is that if each functional silo achieves its target, it automatically

translates to achieving the whole system's target (Dimmick-Touw, 2019). Focusing on the parts of the system in isolation (functions) restrains the significance of relationships among the elements and how they collaborate. Systems fundamentals indicate that the whole is greater than the parts' sum.

Physical conditions and material characteristics are heterogeneous; therefore, variation is inherent in the system. Poorly managed and understood variation leads to misalignment of the system.

2.7 Motivation for a Systems Thinking Methodology for Mining Operations

2.7.1 Global perspective

The global mining industry is evolving; therefore, the South African mining industry must be competitive. South African minerals and metals production decreased, with increasing global economic uncertainties. The mining industry is becoming more digitised, innovative technologies are emerging, and there is a growing interoperability need.

Innovative technologies will ensure easier problem-solving; however, randomness, irregularities, and disorder emerge as the systems and the environment evolve (Alaoma & Voulvoulis, 2018). The constraints are constantly shifting in any mining operation. Adopting innovative technologies does not guarantee a return on investment if mining companies lack an understanding of their mining systems' architecture, behaviour, variability, and flow.

2.7.2 Managing the mining value chain

According to Skyttner (2001), managing a supply chain from a flow perspective creates an understanding of the crucial business drivers, resulting in aligning expectations with the actual performance. Skyttner's statement applies to a mining value chain perspective because understanding the value chain from upstream and downstream flow perspectives help identify key value drivers and leverage points at all levels of the organisation; this enables management to approach underperformance effectively. The instabilities in the system may ripple along the value chain if ineffectively managed by buffers owing to the interdependent nature of activities, processes, information flow, and resources (Claassen, 2015). The ripple effect is more significant as it shifts from the source, leading to a substantial influence system (Fowler, 1999; Towill, 1998; Forrester, 1958).

2.7.3 Integration in the system

Mining is dynamic, and the value chain should be managed according to flow-based principles; therefore, synchronising resources and the visibility of the total mining system is critical to managers and operators (Claassen, 2015). Claassen (2015) further adds that valuable resources are wasted due to the lack of integration and understanding of the flow constraints, determining the system's output. This lack causes inadequate capital allocation and productivity of the resources. The benefits of the STA include understanding and managing constraints, dependencies, variables, behaviours, and the mining system's flow

(product, information, financial resources, demand, and forecast) at various levels of the organisation.

The fundamental principles of how mining comprises interconnected elements with diverse characteristics and behaviours, achieving a defined and measurable goal, must be understood and practised. The visibility of the holistic mining system is usually fragmented along departmental boundaries (Claassen, 2015). Understanding the CCR, the flow in the system, and the variability's influence is critical to effectively designing and managing the system to maximise its performance (Lane, 2018). A systems approach can be a technique to:

- Understand non-performance from a mine planning perspective;
- Improve process efficiencies and synchronisation activities;
- Understand flow and variability across the value chain;
- Understand the behaviour of the operation and the emergent properties;
- Improve and integrate processes downstream and upstream;
- Learn from incidents; and
- Effective resource use while maximising ore use (Lane, 2018).

2.8 Complex Environments

In complex environments, problems and decisions require operational understanding; however, the thinking process approach limits problem

knowledge (Jambekar, 2000). ACM aims to meet planned production targets at a minimal cost within a specific period. This has to be achieved in an environment with complex geology, inconsistent human behaviour, variable equipment and processes, and variable markets (Uludag & Pretorius, 2018). Core problems, such as causes of recurring patterns and underlying structures behind trends, are well understood and processed effectively when operations are recognised as systems, therefore, providing long-term value solutions (Uludag & Pretorius, 2018).

In complex environments, systems thinking offers techniques enabling functional walls to be fragmented by creating a framework facilitating interconnection among various functions (Jambekar, 2000). This approach is required to overcome decision-making and information processing limitations (Weissenberger-Eibl, et al., 2019). An STA integrates technical, economic, environmental, and social values and performance (Mottola, et al., 2007).

2.9 Applications of Systems Thinking in Mining

Systems thinking is not adopted widely in mining operations to improve the system's efficiency; however, the following case studies emphasise the efficiency of this approach to problem-solving. This thinking approach benefits optimising processes and services, effective decision-making, understanding feedback, and stabilising a system.

Alaoma and Voulvoulis (2018) studied how resource-active regions can manage natural resources from a systems thinking perspective. Alaoma and Voulvoulis

(2018) urges that this approach exposes the critical divergences and barriers, undermining efforts to extract and manage natural resources sustainably.

2.9.1 Yield improvement at a coal mine

Claassen (2013) conducted a case study of the yield improvement at a mid-sized coal mine, adopting a flow principle. The relationship between the ore morphology and the plant processing subsystems was emphasised. Claassen (2013) added that unpredictability geologically complex characterise mining environments. Linking geological properties with the downstream processing properties improved system integration and developed a condition-based planning standard for the operation. The system's stability improved when adopting material flow, becoming more predictable. A 30% improvement in the throughput and plant performance was observed (Figure 8).

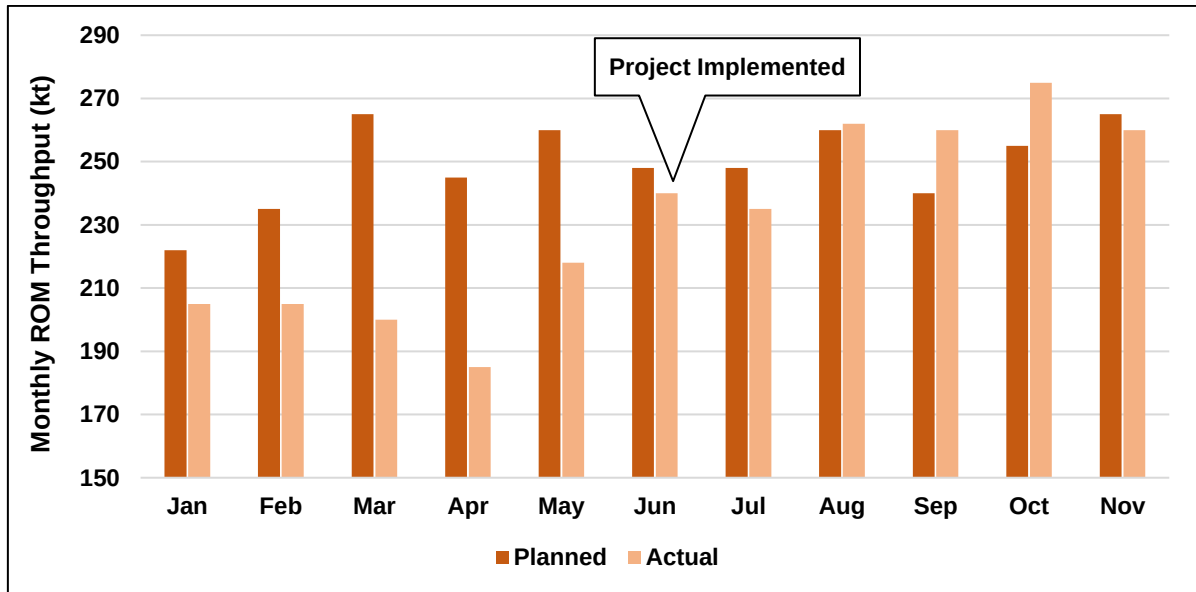


Figure 8. Improvements in throughput after implementing systems thinking flow observation of the ore morphology and geoprocessing (Claassen, 2013).

2.9.2 Safety leadership

Leveson (2011) remarks that preventable accidents and incidents with similar system causes recur. This recurrence is because of failure to learn from the past and to change accident responses. The interfaces among functioning systems can lead to accidents in complex systems.

Donovan, et al. (2017) conducted a case study relating to a landslide at a mining operation in the United States of America, adopting systems thinking in safety leadership. There were no fatalities after the incident, creating a platform for learning from the resulting positive outcomes. The study's findings confirmed safety leadership as an emergent characteristic of complex socio-technical

systems. Multiple human and non-human factors enabled and supported decision-making.

The incident analysis revealed that multiple actors' decisions affected the system's response to the landslide. Donovan et al. (2017) emphasise that safety leadership comprises several factors—not a single action or decision; it relies on vertical integration across various system levels. Integration supported the feedback across multiple levels.

Donovan et al. (2017) confirms that adopting the STA to safety leadership had advantages over traditional methods; therefore, examining the network of links between each influencing factor, decisions, and actions before the landslide helped shape system performance. A resilient system enabled a rapid return to normal. The fundamental concepts of systems thinking, such as vertical integration, should be a critical focus area (Donovan et al., 2017). The control spread attributable to vertical integration across multiple levels of work was recognised within the socio-technical systems (Donovan et al., 2017; Flach, et al., 2015; Reiman, et al., 2014).

Leveson (2011) states that complex systems are more complicated for operators to manage. Donovan et al. (2017) emphasise that integration results in efficient crisis management. Feedback was vital in the build-up and outcome of events. The landslide was an external factor that could not be prevented. No efforts were taken to avoid the landslide. To remedy the situation, the mindset shifted from

redirecting the focus (from activities expected to prevent the landslide) to determinedly planning for failure emerged (Donovan, et al., 2017).

2.10 Conclusion

This chapter emphasises the complexity of mining as an organic organisation; therefore, it cannot be managed similar to mechanistic environments as it employed the functional approach (silo approach), best practices, and strong hierarchical authority. The silo approach emanated from the mine development and planning phases of the mine life cycle. The manufacturing improvement methods cannot solve mining challenges as the industries vary.

The subsequent chapter reviews the literature from the MRTM perspective, emphasising the traditional mechanistic approach's shortcomings. The system's value chain and drivers' management while integrating the critical performance areas (CPAs) with their influence areas are discussed.

3 SYSTEMS THINKING THROUGH A MINERAL RESOURCE MANAGEMENT PERSPECTIVE

3.1 Introduction

This chapter extends the literature review by interrogating the traditional method of managing a mineral resource and the value chain. Emphasis is on managing crucial value drivers from a systemic observation, using value driver models. This chapter discusses the planning process, optimising the mining value chain from mine to customer. MRTM has characteristics of an organic system rather than a mechanistic system. Arguments of why the mechanistic approach is flawed are drawn. CPA synchronisation and its influence areas from flow-based management are reflected.

3.2 The Mining Value Chain

The value chain (

Figure 9) is the backbone of a mining organisation and is a significant source of competitive advantage (McKinsey & Company, 2020). To establish a flow-based view, the primary mining value chain and critical secondary chains must be visible; this is essential in assisting managers and operators in managing the mining system flow (Claassen, 2015). The value chain visibility permits participants to understand how their actions influence the dynamics of the entire system (Jambekar, 2000).

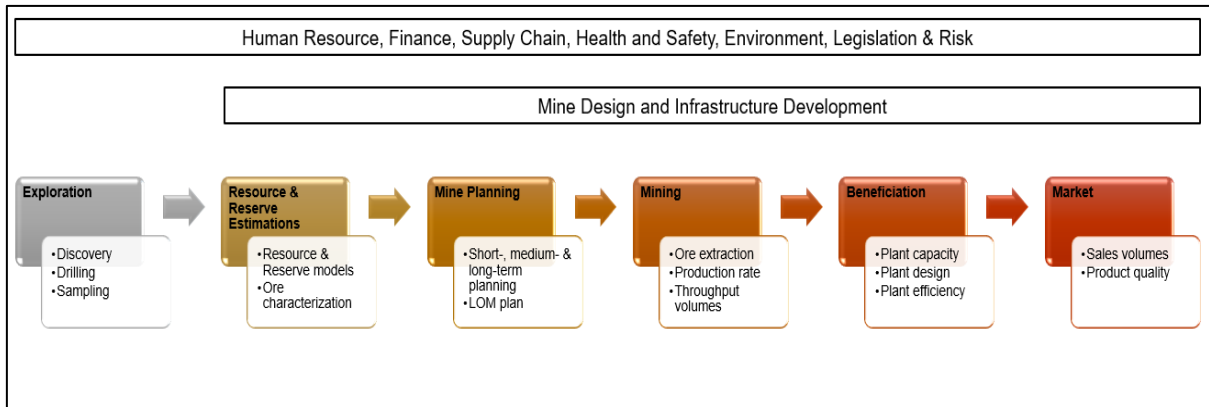


Figure 9. The mining value chain and supporting divisions.

According to Buckerdge, et al. (2010), limited mining companies implement a planning process that optimises the mining value chain from mine to customer. Historically, comprehensive value chain management has been neglected. This carelessness resulted in a silo approach with organisational silos. This engagement optimised individual departments rather than the whole operation, therefore, limiting coordination and data transfer (McKinsey & Company, 2020). A greater understanding of the value chain allows organisations to value performance and unlock the potential of the entire system, rather than individual departments independently.

Complete value chain integration can increase earnings before interest, tax, depreciation, and amortization (EBITDA) by 10% to 15%, optimising throughput and operating costs (McKinsey & Company, 2020). Classen (2015) supports this observation in a case study of a coal mining operation using a systemic flow-

based approach integrating the mineral value chain from geology to the plant to improve the yield.

3.3 Value Drivers

Value drivers are interconnected leverage point variables, ensuring the system creates value for stakeholders. Creating exponential value over time is every company's goal; therefore, significant value drivers must be recognised to enable the company to develop financial strategies, optimising value creation (MacDiarmid, et al., 2018).

Value drivers are dynamic and can change with fluctuating economic conditions; therefore, mining companies must identify key value drivers periodically (MacDiarmid et al., 2018). Organisations must have a clear plan for differential value creation rather than complete reliance on commodity prices (Krinks et al., 2011). MacDiarmid, et al. (2018) analysed value drivers for four major mining companies; the findings included revenue, EBITDA multiple, and commodity prices as the primary enterprise value drivers.

Sustainable value creation depends on key value driver management and understanding and the system architecture. Mining companies must build core competencies by exploiting and integrating the value chain and understanding the variability and flow of the system. Prahalad and Hamel (1990) describe core competence as "A collective learning in the organisation, especially coordinating diverse production skills and integrating multiple streams of technologies". The

authors further added that core competencies are developed through continuous improvement to create sustained value.

3.3.1 Value driver models

Value driver tree models uncover fundamental principles of managing complex systems (Cambitsis, 2013). They demonstrate activities cannot be managed in isolation to increase system throughput. The key performance indicators (KPIs) must be synthesised and aligned across various disciplines in a mining production system.

3.4 Mineral Resource Throughput Management

The complexity of mining increases even more as good quality deposits deplete, resulting in increasing risks and decreasing ore grades. The former leads to complex geology (geometry, mineralogical and structural variabilities), variable mining processes (equipment, mine development, and production scheduling), moving bottlenecks, and varying plant feed qualities (Dimmick-Touw, 2019). This affects the system flow and its stability, which may render the system unpredictable. Excellent management and integration of the value chain are essential.

According to Claassen and Laurens (2016), increasing and sustaining profitability is one challenge for mining operations. The authors confirm MRTM as a methodology with immense potential to be fit for mining management and improvement. MRTM has characteristics of an organic system (riddled by

complexity) rather than a mechanistic system, as illustrated in Table I. The MRTM approach aims to increase business performance by increasing the throughput and overall system performance, focusing on the mining value chain (Dimmick-Touw, 2019). The primary purpose is to create sustainable growth and maximise income by ensuring the system reaches its full potential.

Table I: Evaluating the mechanistic approach to mining compared to the systemic approach (Modified after Claassen & Laurens, 2016).

Mechanistic mining approach	The justification why this belief is flawed	MRTM/systemic approach
Mining systems are divided into departments, and the contribution of the departments yields the final product. Costs and raw material values are allocated per stage as the material moves through various stages in the system.	Only the final product produced is sold to the customer, and income will be generated.	The focus is on the rate at which income is generated (maximum production rate and optimal product payability) by the system.
Raw material characteristics can be blended to obtain an average blend that would not	Raw material characteristics, such as hardness, porosity, and textural aspects. Cannot be blended. For	Only material that behaves similarly in downstream processes (compatible material) is blended. The material's physical flow and

Mechanistic mining approach	The justification why this belief is flawed	MRTM/systemic approach
destabilise downstream processes.	example, a mixture of hard and soft rock will not produce a medium-hard rock blend.	product payability behaviour in downstream processes are considered.
The system capacity is equal to the powers of individual resources when the resource capacities are balanced. Resources are allocated based on capacity requirements.	Statistical to perform individual resources and the dependency between resources in a system cause the system to operate below the balanced capacity value.	The capacity of a system is equal to the capacity of the CCR. Capacities are not balanced, but the flow in the system is balanced. Resources (people, equipment, capital) are allocated based on flow and product payability needs.
Fixing a broken/ underperforming part in a system will linearly improve the system's output.	Suppose the constraint in a system is not established using flow and product payability principles. There, there are increased chances that the constraint's performance will not improve, and, therefore,	Determine flow and product payability attrition drivers. Attention is directed towards resolving these concerns.

Mechanistic mining approach	The justification why this belief is flawed	MRTM/systemic approach
	the system performance will not improve as expected.	
An equal focus on the distinct parts/departments of a system will ensure optimal system performance.	The CCR determines a system's performance. Resources and time not directed towards the CCR are wasted. This approach also creates prioritisation conflicts that negatively affect system performance.	Focus is on the constraints' performance, PAY attrition drivers, and the system's output. Synchronising the entire mining value chain (including raw material needs) will ensure optimal performance.
An equal improvement focus on all parts of the organisation will ensure sustainable improvement.	This improvement approach over the long-term balances capacities, which reduces a system's output over the longer term.	Improvement initiatives focus on synchronising the total system. Specific attention to the CCR performance and limiting product payability attrition. System performance elevation through capital expenditure does not disturb

Mechanistic mining approach	The justification why this belief is flawed	MRTM/systemic approach
		the flow balance and increases product payability attrition.
Averaged data will accurately describe a complex environment.	Averaging data in a complex environment hides the inherent complexity of the environment (variability in data is unclear).	Only data from compatible environments (from the same population) will be averaged. The data always reflects the inherent complexity of the relevant environments.

Bender (2005) remarks that realising collaborated solutions in an integrated decision-making process is the critical success factor for any MRTM solution. This can be achieved by integrating the whole value chain (from exploration to market) and vertical integration of information flow for sound decision-making across all levels of the organisation. Several operations experienced business improvement initiatives focusing on solutions approaching the problem symptoms. They, therefore, yield short-term solutions, unsustainable in the long-term; however, some initiatives yielded financial benefits (Bender, 2005). Others focus on procedural improvements instead of the flow-based principle of an optimised mine-to-mill integrated system (University of Antofagasta, n.d.).

Claassen (2016) recognises that a traditional throughput management methodology's shortcoming is the inability to oversee the variability of the raw material in the system compared to an STA. This inevitably influences the throughput effectiveness, downstream processes, and the system's performance. Operations rarely consider the compounding effect of the dependencies, concurrently influencing the system.

3.5 Condition-driven Standards and Ore Body Classification

The traditional approach-based targets disregard system variability (Laurens, et al., 2020). The MRTM approach considers variability by developing condition-driven standards directly connected to geological and processing conditions (Claassen & Laurens, 2016 and Laurens, et al., 2020). This includes classifying the ore body into the three dimensions (physical material flow, product payability, and logical decision-making). The orebody is classified according to in situ chemical parameters, in situ physical parameters, material behaviour through the system, material influence on process efficiency, and mining conditions (Figure 10).

The classification system creates a platform to interrogate and understand each parameter's influence on the system's throughput (Laurens, et al., 2020). It also aids in managing material through the system and the reaction of the variables. The variables' behaviour within the system has diverse influences on the throughput and performance of the entire system.

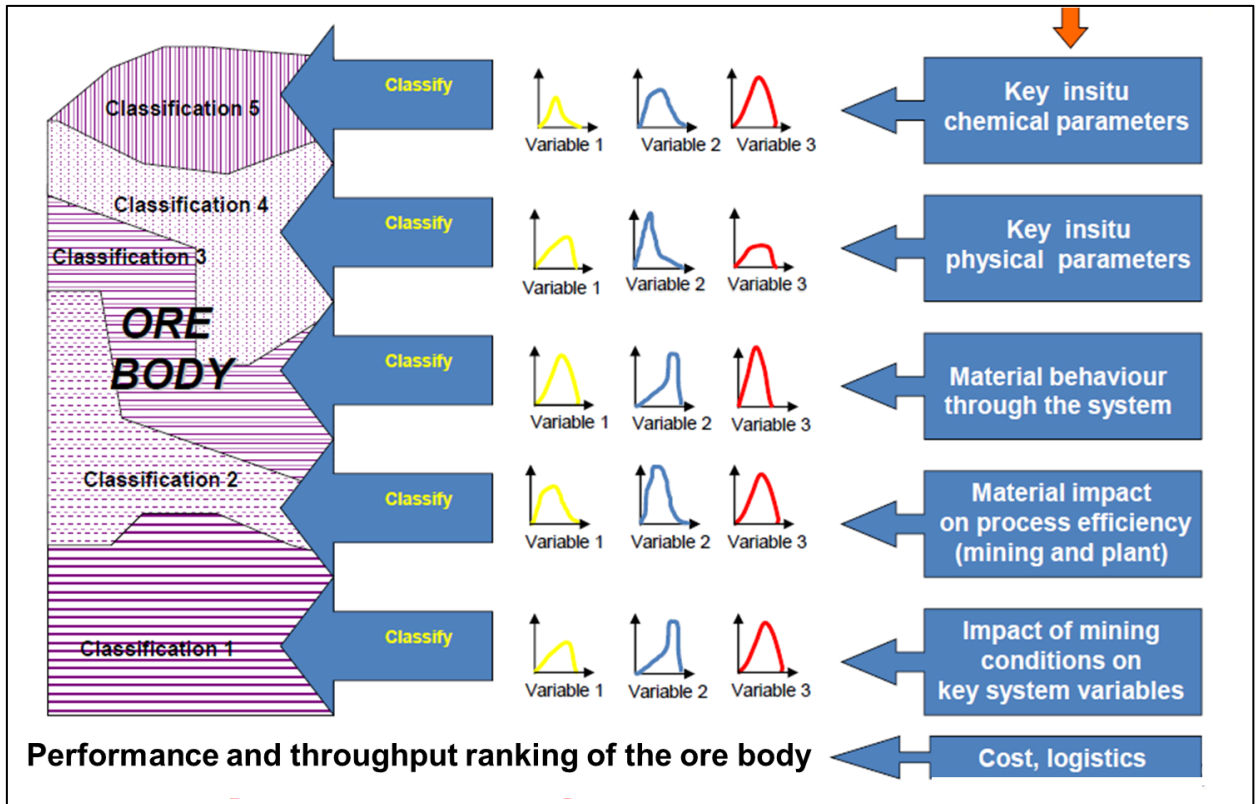


Figure 10. Simplified performance and throughput ranking of an orebody based on the five multiple reaction monitoring principles (modified after Claassen & Laurens, 2016).

3.6 Key Performance Indicators from an MRTM Perspective

Key performance indicators (KPIs) are defined as measurable standards critical for the business' success agreed upon within an organisation (Dougall & Mmola, 2014). KPIs measure departments' and individuals' performance within an organisation (Dougall & Mmola, 2014). Performance measurements are established for compliance, understanding, refining targets, and managing departments and individuals' output (Dougall & Mmola, 2014; O'Neill, 2007).

Silos managed mining companies, have each department focusing on and managing KPIs specific to their control area (Lane & Wylie, 2014). Therefore, CPAs and KPIs are not integrated across the value chain. The production variables (CPAs) influencing the entire system across the value chain are not considered in an integrated approach to understanding their influence areas (Table II).

Table II: An example of production variables and their influence areas (KPIs) across the value chain (modified after Laurens, et al., 2020).

Critical performance areas (Production variables)	Key performance indicators (Influence areas)
Mining dilution / contamination	Production rate of mining and plant, extraction percentage, beneficiation potential, beneficiation efficiency, plant yield, production cost, product loss, income, product quality, product quantity, ROM quality, cut-off parameters, maintenance, life-of-mine (LOM), ore use.
Slimes / super fines	Beneficiation potential, beneficiation efficiency, product loss, plant yield, production cost, income, product quality, product quantity, ROM quality, cut-off parameters, and ore use.
Physical mining and geological conditions	Production rate of mining and plant, dilution/mining dilution, fines loss, extraction percentage, beneficiation

Critical performance areas (Production variables)	Key performance indicators (Influence areas)
	potential, beneficiation efficiency, plant yield, production cost, income, product quality, product quantity, ROM quality, cut-off parameters, mining method, system use, maintenance schedules, ore use.
Mining extraction percentage	Production rate of mining, production cost, ore loss, income, product quantity, stripping ratio, cut-off parameters, LOM, and ore use.
ROM quality	Production rate of mining and plant, extraction percentage, beneficiation potential, beneficiation efficiency, plant yield, production cost, income, product quality, product quantity ROM quality, cut-off parameters, ore use, and plant design.
Material compatibility	Production rate of mining and plant, extraction percentage, beneficiation potential, beneficiation efficiency, plant yield, production cost, income, product quality, product quantity or quality, cut-off grade, ore use, plant design, and market.
Beneficiation	Product loss, product type, product delivery (volume and quality), physical product characteristics, beneficiation potential, beneficiation efficiency, cost, income, total

Critical performance areas (Production variables)	Key performance indicators (Influence areas)
	process efficiency, throughput, market demand, mineral association, and material compatibility.
Plant yield	Production rate (mining and plant), cut-off grade, project valuation, beneficiation potential, beneficiation efficiency, plant design, product type, product quality and quantity, market, process efficiency, plant design, and mineral association.
Optimum product qualities	Production rate (mining and plant), cut-off grade, project valuation, beneficiation potential, beneficiation efficiency, plant design, product type, product quality and quantity, market, process efficiency, plant design, mineral association, and material compatibility.

3.7 Conclusion

The value chain visibility is emphasised with an enormous influence, permitting participants to understand how their actions affect the dynamics of the entire system. Equal improvement focus on all parts of the organisation does not ensure sustainable improvement; therefore, complete integration of the value chain and processes can increase EBITDA by 10% to 15% by optimising throughput and operating costs. The key production variables (CPAs) influencing the entire system across the value chain should be synchronised.

MRTM aims to increase business performance by increasing throughput and overall system performance. MRTM focuses on the mining value chain as a system with the potential to be fit for mining management and improvement. The subsequent chapter explores the systems thinking framework and the MRTM methodologies.

4 METHODOLOGY

4.1 Introduction

This chapter explores the methodology adopted for this research, employing qualitative and quantitative research techniques. The systems thinking methodological framework is integrated with the MRTM principles endorsed by Claassen and Laurens (2016). The qualitative methodology entails interpreting, analysing, and evaluating historical information.

4.2 Systems Thinking Methodology

According to Cavana and Maani (2000), the methodological framework for systems thinking encompasses five phases:

- Problem structuring;
- Causal loop modelling;
- Dynamic modelling;
- Scenario planning; and
- Implementation and organisational learning.

This study applied the above phases, holding a wide range of applications. The framework can apply to designing new systems and improving existing systems. The framework can also be beneficial to predict a complex system's behaviour (system archetypes) under dynamic conditions and understand subsystems' interactions (Cavana & Maani, 2000).

4.2.1 Problem structuring

The problem area and objectives were defined. Historical information from when the mine was in full production before mine closure (2015) was analysed to identify inefficiency in the system; to an extent, this demonstrates the shortcomings of a deterministic approach to operating a complex system.

4.2.2 Causal loop and dynamic modelling

This phase applies critical thinking by drawing inferences from all system parts, relating to the problem in the previous phase. These steps were, therefore, followed by causal loop modelling:

- The main variables were identified;
- Illustrated the relationships among the variables;
- Depicted behaviour of the main variables over time;
- Identified the system archetypes; and
- A systems diagram was developed, indicating the main variables.

Systems dynamics software, Vensim, generated a causal feedback loop diagram, illustrating variables and their relationships. Vensim presents variables, stocks, and flows graphically to outline and visualise complex problems. A causal loop diagram demonstrated non-linear interactions and the dependency of variables

in the system. This enables understanding of the causes and effects of certain variables and the entire system's feedback structure.

The systems' dynamic model interrogates feedback effects while combining qualitative and quantitative methods to understand behaviour. The model examines how the system structure can cause the holistic behaviour of the system while integrating the flow and feedback loops in the system.

Figure 11 is an example of a simple casual loop diagram. A causal loop diagram comprises arrows and feedback loops. The arrows indicate the causality direction (Jackson, 2003). Each arrow contains a positive (+) or negative (–) sign, indicating the relationship polarity. The (+) arrow demonstrates that an increase in the independent variable increases the dependent variable (and a decrease causes a decrease in the dependent variable) (Jackson, 2003); for example, increasing performance increases effort. The (–) arrow denotes that an independent variable increase causing the dependent variable to decrease. An increase in the constraint upsurges the limiting action, therefore, an increasing limiting action reduces performance.

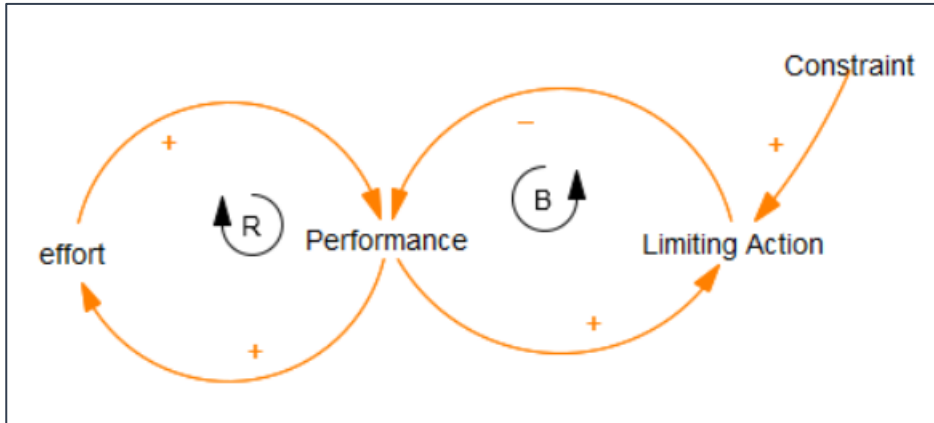


Figure 11. An example of a causal loop diagram.

The two types of feedback loops include a balancing (B) and a reinforcing (R) loop. These loops signify the behavioural patterns produced by the system. A balancing loop is determined by an odd number of negative (-) links, whereas a reinforcing loop has an even number of negative (-) links. A balancing loop produces oscillation or resists an increase in a certain direction, therefore, attempting to maintain equilibrium (Lannon, 2018). Conversely, a reinforcing loop produces exponential growth or decline (Jackson, 2003).

4.2.3 Scenario planning and dynamic modelling

A value chain integration model was constructed to indicate the influence of the physical and chemical properties of the orebody on the raw material flow and processes across the value chain. Microsoft Excel was used to generate scenarios by considering diverse variables.

Three scenarios are modelled from four sections, representing various geological conditions. Historical conditions generated from grade control reports are the basis. The model indicates the influence of contamination on processes across the value chain and the influence on costs. The model demonstrates material flow in the system. The model calculations and inputs are detailed in APPENDIX A and APPENDIX B. This methodology indicates how the processes are affected, including the effects on the yield and product quality. Based on the challenges encountered by the mine pre-2015, the model illustrates how variability affects yield and product payability.

4.3 Mineral Resource Throughput Management Methodology

The MRTM is founded on the systems thinking theory (Claassen & Laurens, 2016; Claassen, 2015). According to Dimmick-Touw (2019), MRTM integrates variability in physical operating conditions, characteristics of the plant process, and the ore's attributes into the decision-making process and business logic. It considers the interdependencies between variables and critical drivers, integrating them into strategic planning, performance management, and budgeting.

MRTM is based on three dimensions, including physical flow, product payability (monetary value of the product because of volume, quality, and quality consistency), and logical decision-making (comprising elements of the TOC) illustrated in Figure 12 (Claassen & Laurens, 2016). Understanding the raw material's flow and product payability behaviour from the strategic and operational environment is essential. The method aims to create and sustain

value throughout the value chain by minimising losses during mining and processing.

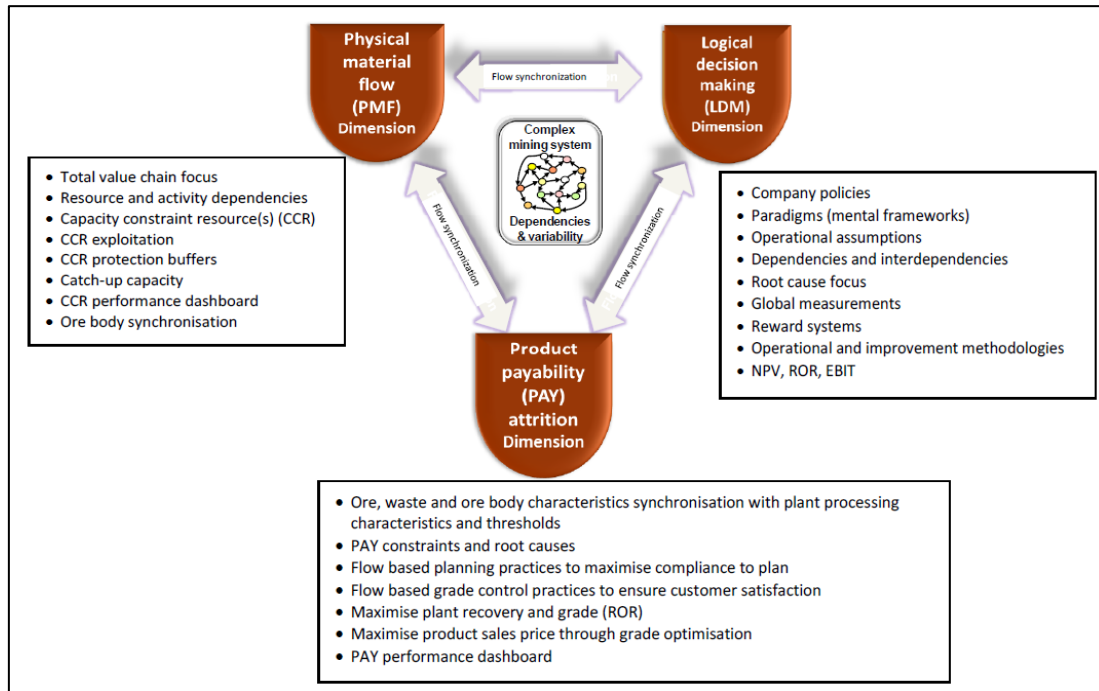


Figure 12. Mineral Resource Throughput Management Methodology dimensions (Claassen & Laurens, 2016).

4.4 Assumptions

The base case is constructed with actual historical data for scenario planning; Scenarios 1 and 2 are optimised figures. The total cost was split into 60% fixed and 40% variable costs. The final product yield and qualities are based on a blending strategy of 40% full beneficiation and 60% crush and screening processes. Throughput constraints and CCR were considered in constructing the model and analysis (further elaborated in 7).

CCR are considered for at an efficient operational level for an optimised system (Scenario 2). For example, the resource model is assumed to have a high level of accuracy and precision. The mine design layout is optimal, and the equipment is within the specification for the ground conditions. Adequate plant and buffer capacity are assumed to ensure material flow within the system.

4.5 Data Sources

Historical information from when the mine was still operating was used in this study. The data were stored in a central database; some information was extracted from grade control and production reports. The seam distribution maps were created from borehole information using Geovia Minex software.

Limited data were available for this case study. Some information from critical departments within the value chain was unavailable on the database, such as historical mining and plant data.

4.6 Conclusion

This chapter summarises the hybrid methodologies in this research. The five phases of the systems thinking framework with the three dimensions of MRTM were considered. The subsequent chapter presents the results and data analysed, using the foundations established in this chapter. Historical throughput and quality data are analysed to draw findings.

5 DATA ANALYSIS AND RESULTS

5.1 Introduction

This chapter presents historical data and results. The data were sourced from the ACM database. The physical and chemical characteristics causing the raw material variability and processes are demonstrated. The relationships and dependencies among the chemical and physical characteristics of the coal are analysed, using throughput and quality trends.

5.2 Resource and Reserve Statement

The resource and reserve statement for the ACM post-closure indicates that there are significant resources to be exploited (Table III). The data are sourced from the 2021 life-of-mine (LOM) plan generated with XPAC mine planning software. In 2020, the total resources and reserves were 153.9 Mt and 48.9 Mt, respectively (Arnot OpCo, 2020). The reserves split per area and coal qualities are in **Error! Reference source not found.**, according to the South African National Standards (SANS) 10320 guidelines.

Table III: The 2020 resource and reserve statement (Arnot OpCo, 2020).

Resources	Mt	Reserves	Mt
Measured	118.03	Proved	43.29
Indicated	18.75	Probable	4.95

Resources	Mt	Reserves	Mt
Inferred	17.11		
Total Resources	153.89	Total Reserves	48.24

Table IV: Reserve Statement and coal qualities (Arnot OpCo, 2020).

Reserve Category	MTIS*	ROM	CV	AS	VM	TS	IM	FC
	(Mt)	(Mt)	(MJ/kg)	(%)	(%)	(%)	(%)	(%)
Proved (OC)	17,82	17,82	24,41	20,35	27,17	0,91	3,85	48,69
Proved (UG)	25,47	25,47	23.00	22,48	25,65	0,86	4,09	47,68
Total Proved (OC+OG)	43.29	43.29	23,81	21,28	26,51	0,89	3,96	48,26
Probable (OC)	4,95	4.95	25,02	17,76	27,50	0,99	4,50	49,97
Total Reserve	48,24	48,24	23,93	20,90	26,62	0,90	4,01	48,44

5.3 Seam Thickness

Physical attributes, such as undulating roof and floor and in-seam partings within S2L and S1 characterise ACM. The minimum mineable seam height cut-off is 1.8m for underground (S2L only) and >1m for opencast (S1 and S2L) based on geotechnical considerations; mining considerations, throughput and efficiency, commercial considerations, as well as modifying factors for both underground and opencast.

Figure 13 illustrates the seam distribution across the mine for S2L and S1. Geological borehole log data generated the seam thickness plots, collected throughout the years until mine closure. Localised changes in the seam thickness are present, where the seam pinches or the dip of the seam changes. The physical properties of the seam are highly variable among areas, also considering geological structures such as faults, dykes, and sills.

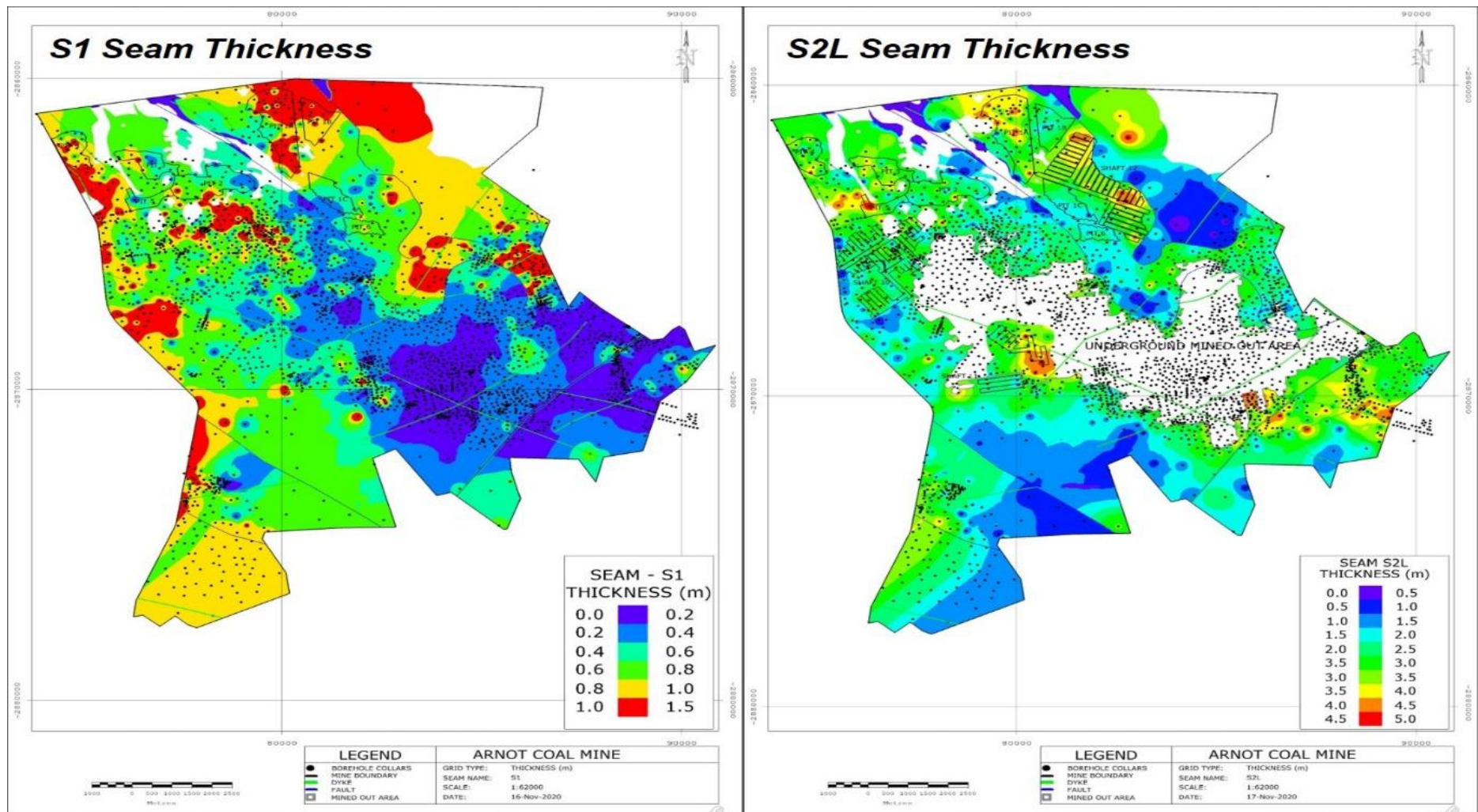


Figure 13. Seam thickness distribution for S2L and S1 cross Arnot Mine (Arnot Opco, 2020).

5.4 Production Profile Pre-Closure

The mine exploited opencast and underground mining methods from 2007 to 2010. In 2011, only underground mining areas was exploited. The throughput of the mine increased from 2007, reaching a maximum of 5.2Mt in 2009 and ramped down post-2009 to 1.4Mt in 2015 when production ceased (

Figure 14). A sharp decrease in production tonnes is established between 2009 and 2011 by over 2.5 Mtpa. Opencast mining ceased in 2010, therefore, resulting in the drop in production tonnes by 45% between 2010 and 2011.

The in-week production was supplemented by zama zama weekend shifts to increase production. Zama zama shifts included mining teams working overtime on weekends at a remuneration rate slightly higher than the average overtime rate to cover weekly production shortfall.

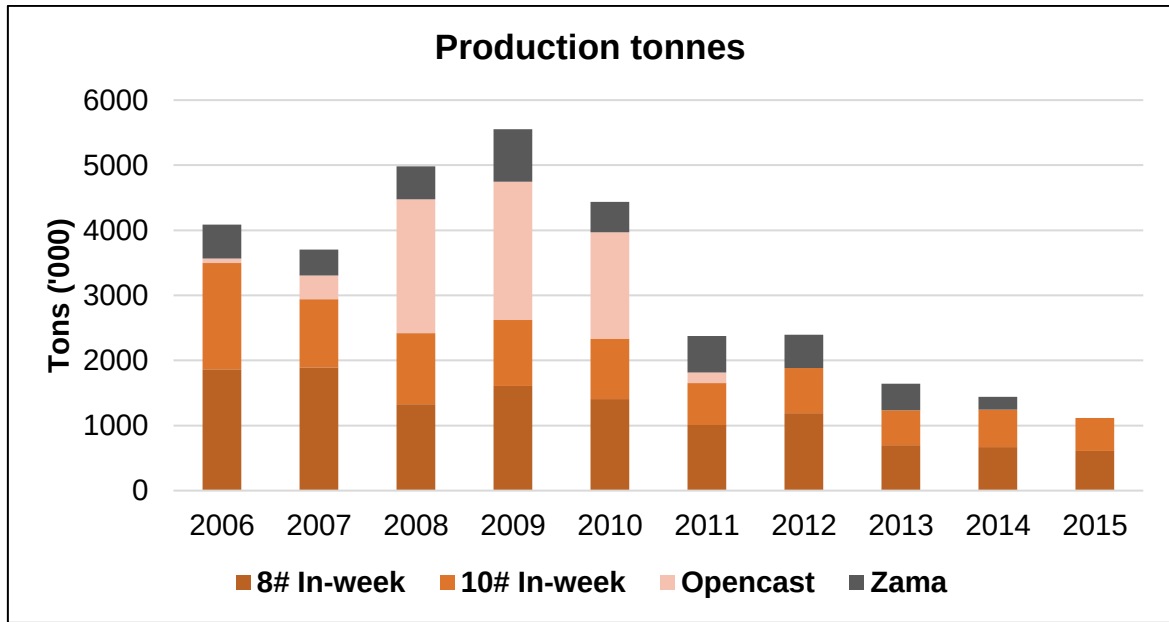


Figure 14. Annual Production tonnes from 2007 to 2015 (Data Source: Arnot OpCo Database).

Figure 15 demonstrates the variation in the monthly tonnes produced from 2009 until 2015. The Mine produced the lowest throughput of 22 Ktpm in March 2013. A sharp decline in ROM tonnes was established between December 2010 and July 2011 after opencast operations ceased. The trend of the graph indicates a ramp down before mine closure.

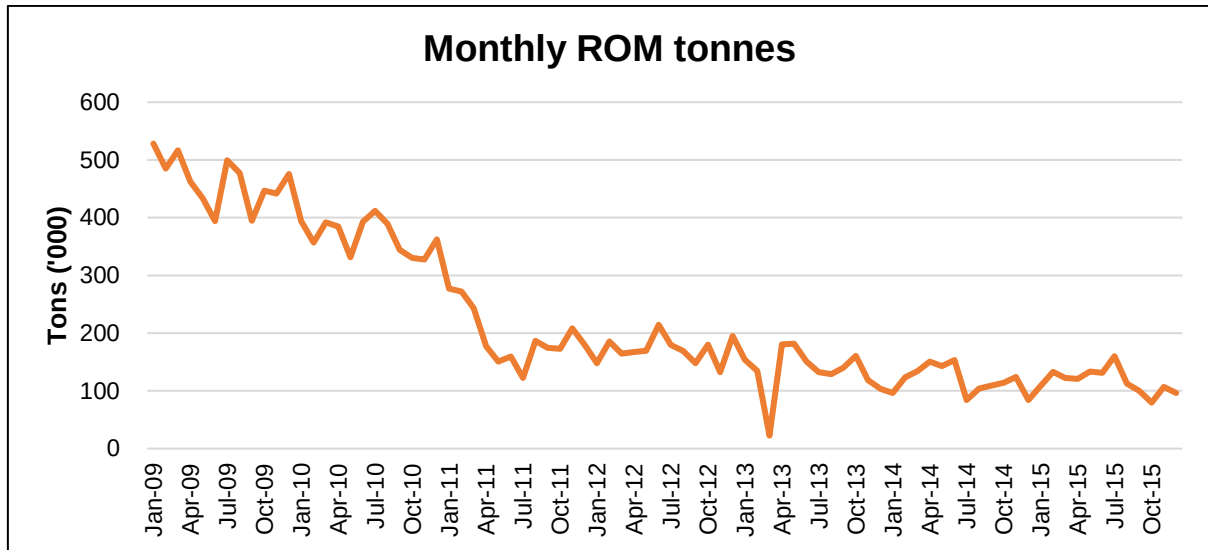


Figure 15. Monthly production tonnes from 2009 to 2015 (Data Source: Arnot OpCo Database).

Since 2010, the mine failed to reach the budgeted annual tonnes (Figure 16) for underground and opencast. A significant variance exists between budgeted and actual tonnes for the underground. This indicates non-compliance with the plans, therefore, targets were not met. The budgeted tonnes decreased from 3.4 Mta in 2010 to 1.7 Mtpa in 2010. This could have been due to a plethora of cumulated operational challenges.

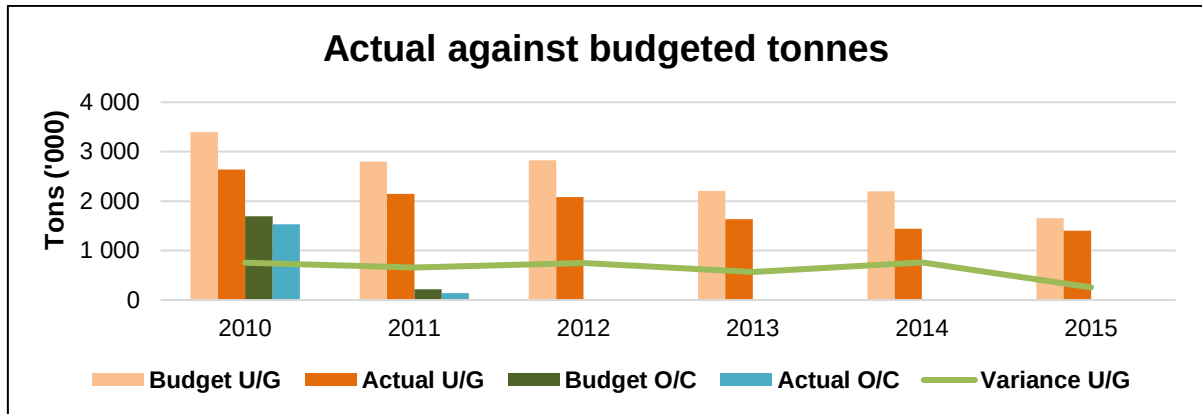


Figure 16. Actual against planned tonnes for underground and opencast from 2010 to 2015 (Data Source: Arnot OpCo Database).

5.5 Waste Produced (Contamination)

Representative contamination data were only available for 2013. Figure 17 illustrates that the total contamination was above the allowable limits of 4% throughout the year. The contamination data were averaged monthly from two underground shafts with seven sections. March 2013 had the highest contamination above the cut-off limit, and the lowest ROM tonnes produced. This was due to producing far fewer tonnages for that month compared to other months.

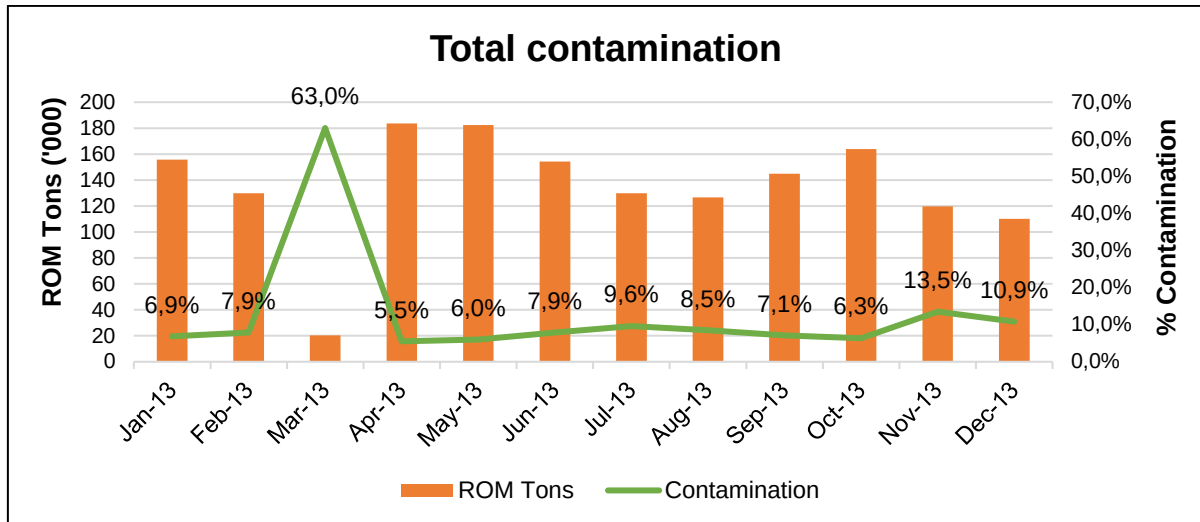


Figure 17. Total contamination for 2013 (Data Source: Arnot OpCo Database).

For most of 2013, the actual total contamination is more than the planned contamination, except in July and December (Figure 18). The average variance between planned and actual total contamination is -23 079 tonnes. The two graphs follow a similar trend between January and May, September, and November.

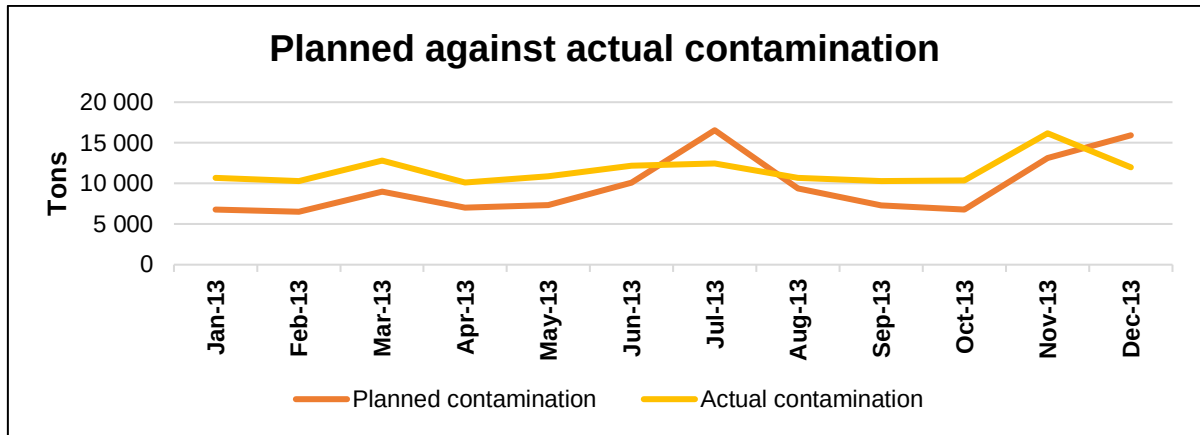


Figure 18. Planned against actual total contamination for underground (Data Source: Arnot OpCo Database).

Figure 19 illustrates contamination cases from the underground. Contamination in the images could have been controlled and managed by enforcing strict grade control and mining standards aligned to integrated KPIs across the value chain.

Figure 19A and 19C indicate overcutting of the roof, comprising mainly sandstone, by over 0.5m. Figure 19A indicates a coal seam height below the cut-off coal seam of 1.8m and a floating stone of 1.2m, due to floor undulations. Figure 19C indicate roof overcutting by 0.7m because of mining practices as the seam height is sufficient for a machine with a 2.20m minimum cutting height.

Figure 19B and 19D indicate cases where there was in-seam parting, and roof and floor overcutting. Figure 19B demonstrates a seam that pinches out and 1.75m of sandstone. The total coal mined is 0.96m; therefore, the sandstone cut exceeds the coal for that mining road. This illustrates localised changes in physical conditions underground and mining practices.

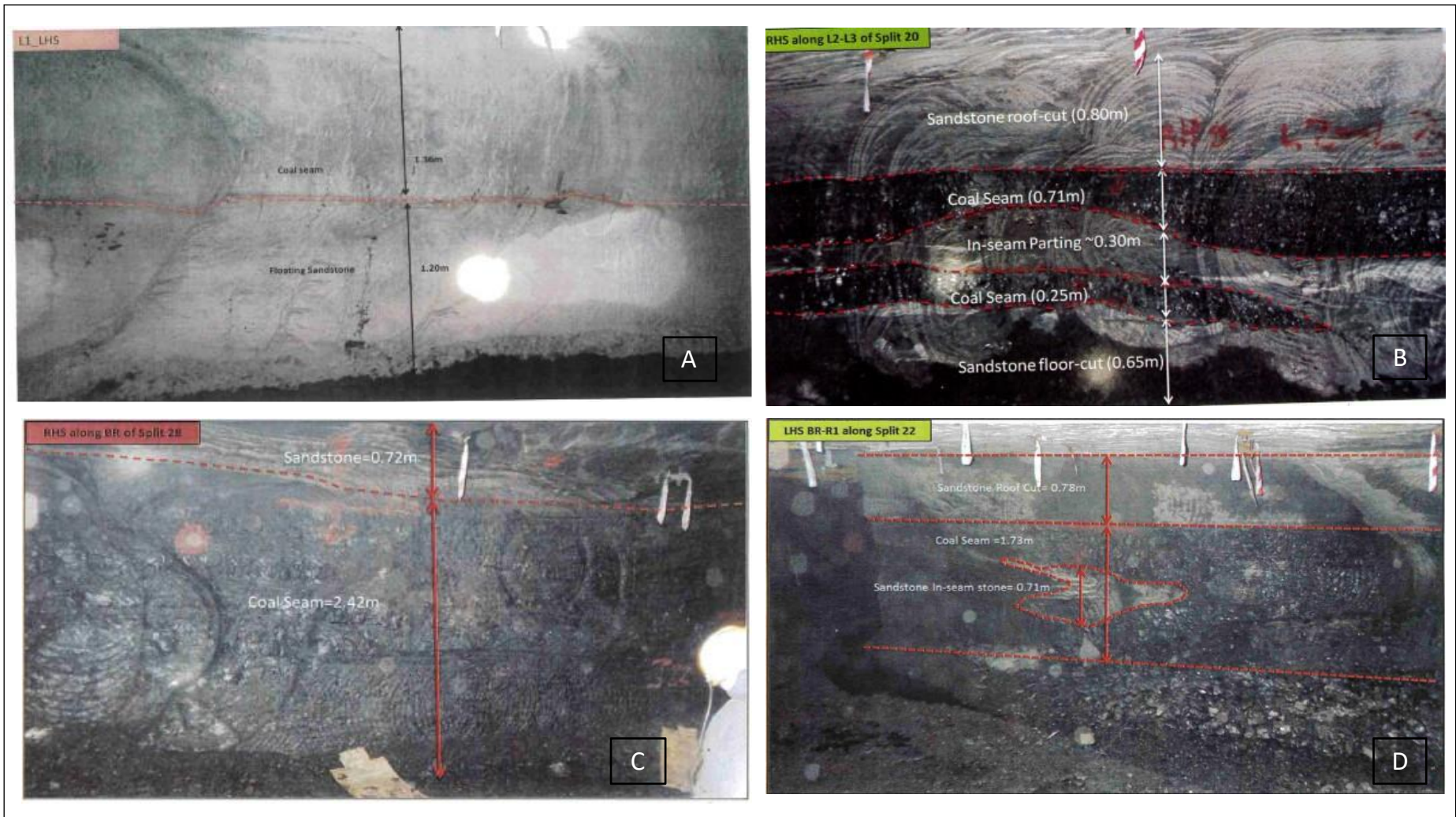


Figure 19. Images of underground mined roads illustrating mined heights (Exxaro, 2015).

5.6 Mining Equipment

Historically, the mining continuous miner (CM) fleet comprised two machines types listed below in Table V. Seven operating CM sections were established; there were no drill and blast sections. Complementary underground section equipment supported the CMs. The minimum cut-off seam thickness was 1.8 m. Joy HM31AAA had a minimum cutting height above the cut-off seam thickness and Joy HM31B was below 1.8 m (Table V). In areas where the seam was below 1.60 m or 2.20 m, excessive roof or floor would have to be cut to make room for the machines, therefore, adding waste to the ROM.

Table V: Continuous fleet before mine closure (Data Source: Arnot OpCo Database).

Machine type	Min cutting height (m)	Max cutting height (m)	Floor dip (degrees)
JOY HM31B	2,20	4,50	6
JOY HM31AAA	1,60	3,80	4

Figure 21. Average mined height for CM HM31B (Data source: Arnot Opco database). and Figure 23 illustrate the mined height per machine in each section. The mined height for both machine types was above the minimum cutting height and below the maximum cutting height.

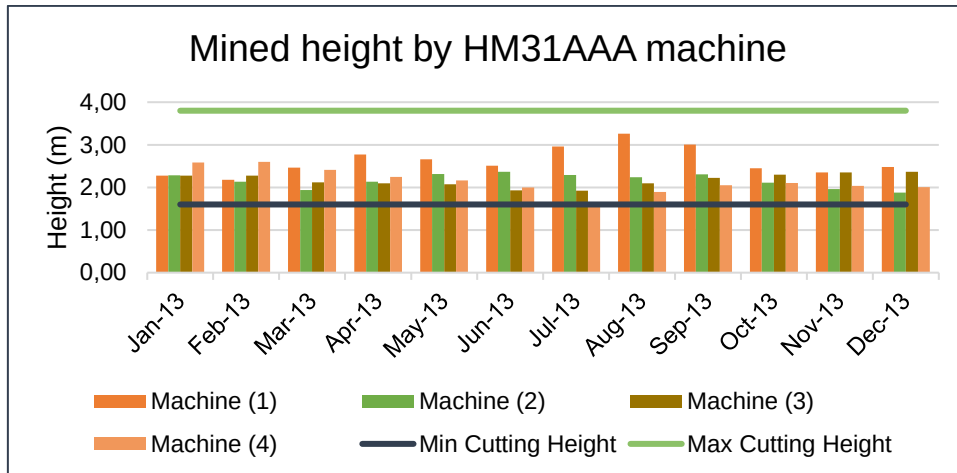


Figure 20. Average mined height for CM HM31AAA (Data source: Arnot Opco database).

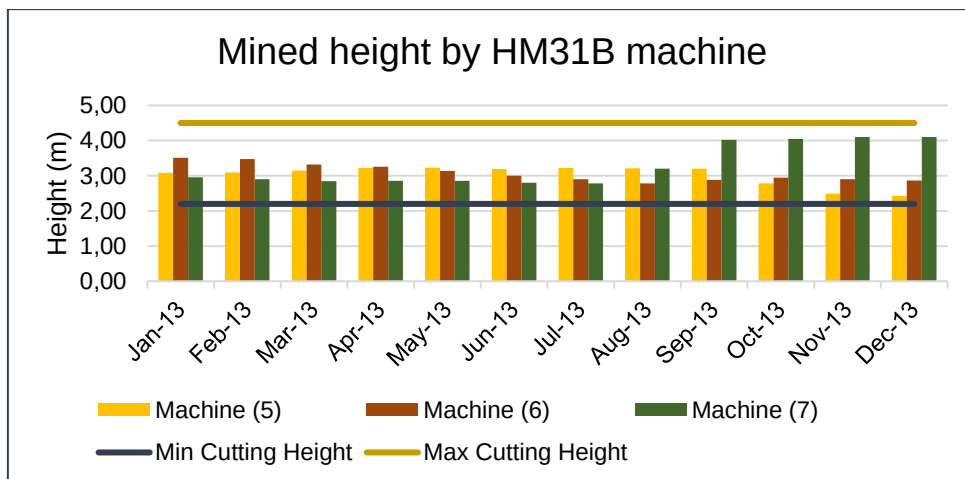


Figure 21. Average mined height for CM HM31B (Data source: Arnot Opco database).

Figure 23 indicates waste mined by each machine per section. All seven machines in each section mined variable waste amounts. The latter could result from:

- Misalignment between the geology, planning, and mining departments;
- Knowledge sharing between grade control and mining teams to ensure the CM operators do not contaminate the coal;
- Misalignment of KPIs (priority to tonnes over yield and qualities); and
- Non-compliance to short-term plans.

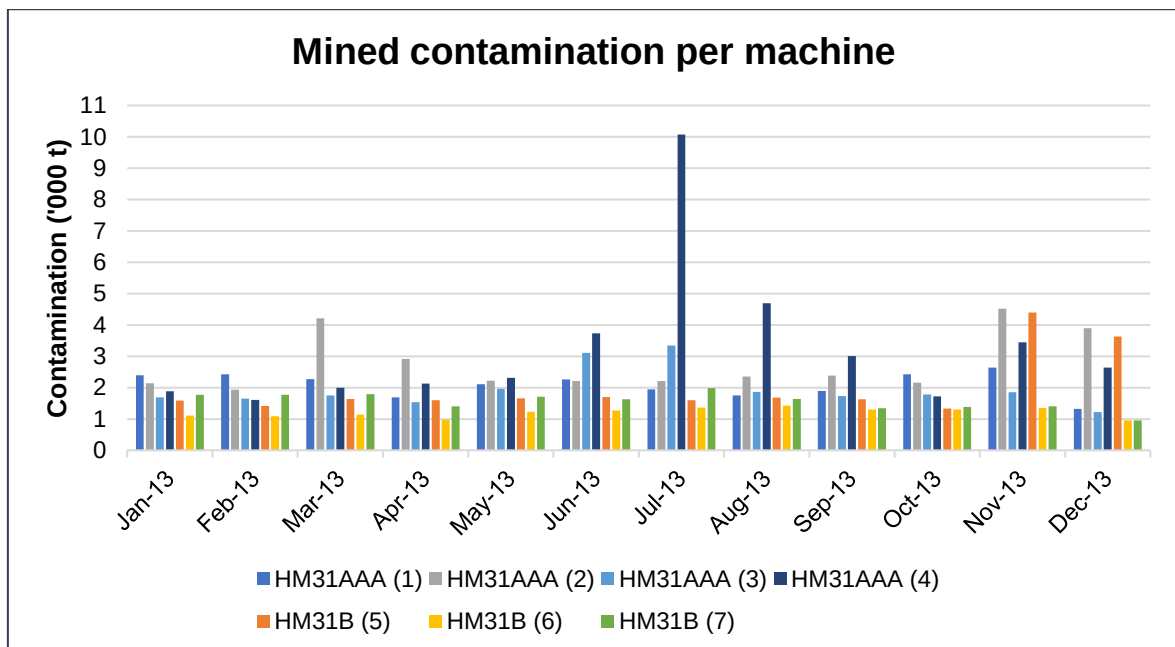


Figure 22. Average mined contamination by CM type (Data source: Arnot Opco database).

5.7 Coal Quality Relationships

The coal qualities data were generated from sample assays from exploration and grade control samples, stored in the geodatabase. The in-situ coal qualities are variable within various reserve areas on the mine. Therefore, the coal qualities are not homogenous across the mine owing to the resource's variable physical and chemical properties. Coal quality parameters have an intricate relationship that must be managed from a beneficiation and blending perspective, to produce the correct product specification.

Calorific value (CV) and ash have an inversely proportional relationship (Figure 23 to Figure 25) Where the CV is higher, the ash content is lower, and contrariwise. The CV and ash properties for S2L are highly variable compared to S1. The coal's volatile matter (VM) is directly proportional to the CV of the coal (Figure 23). The coal is devolatilised where there are sills and dykes, affecting the coal's VM content.

The mineral matter's chemical composition contributes to the ash and RD relationship. Sedimentary rocks comprise silicates; coal comprises organic matter (carbon). The ash percentage represents the inorganic material, usually holding a relative density (RD) higher than coal. Ash, therefore, has a directly proportional relationship with RD (Figure 23).

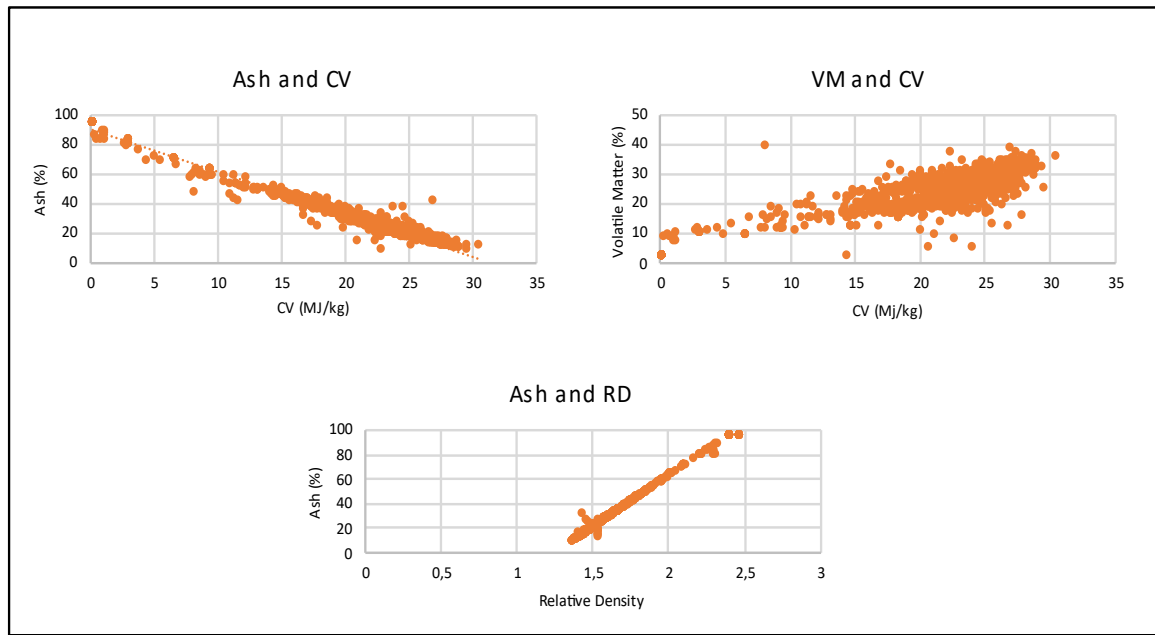


Figure 23. The relationship between coal quality parameters for the Arnot Mine (Data Source: Arnot OpCo Database).

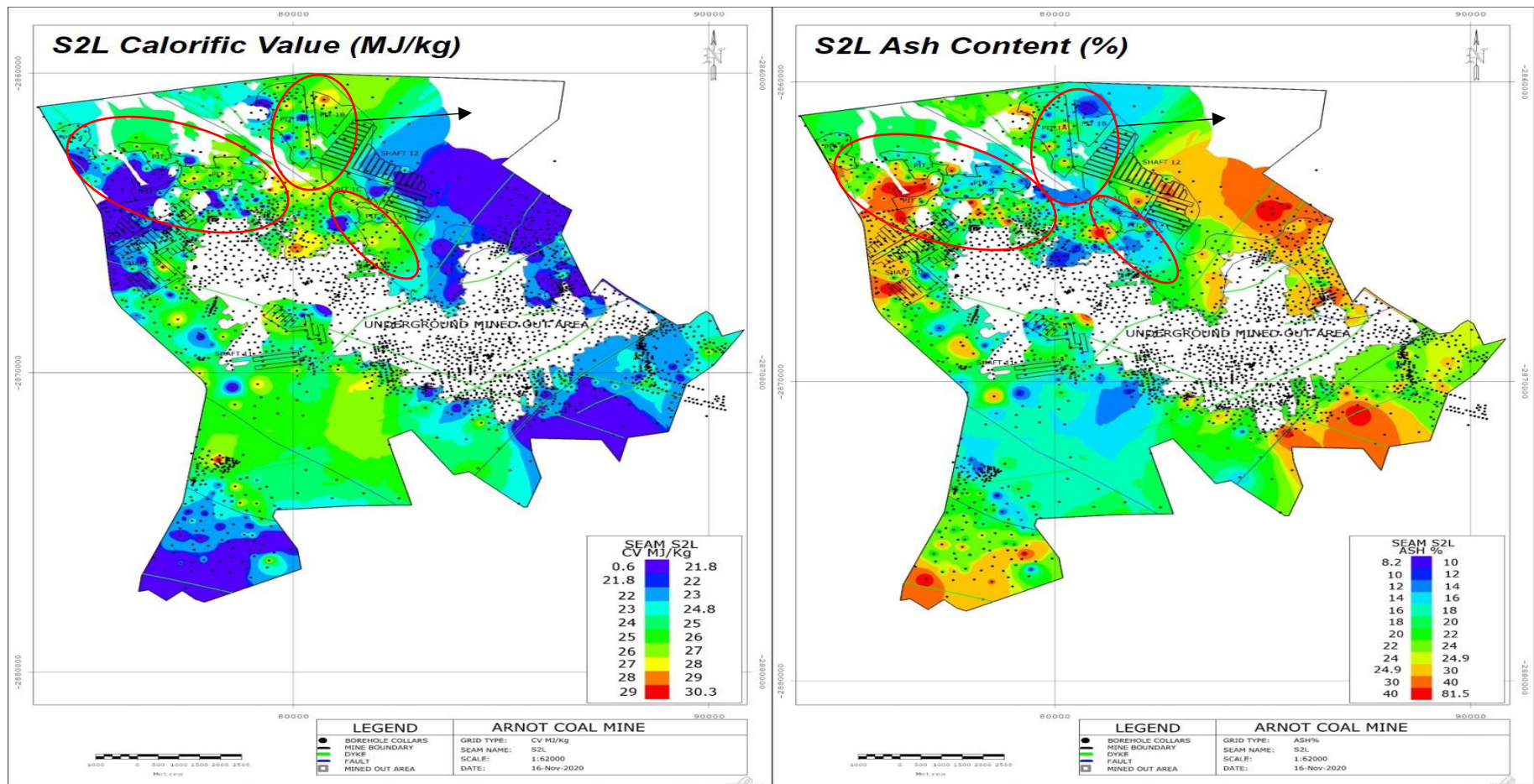


Figure 24. Calorific value and ash plots for S2L (Arnot Opco, 2020).

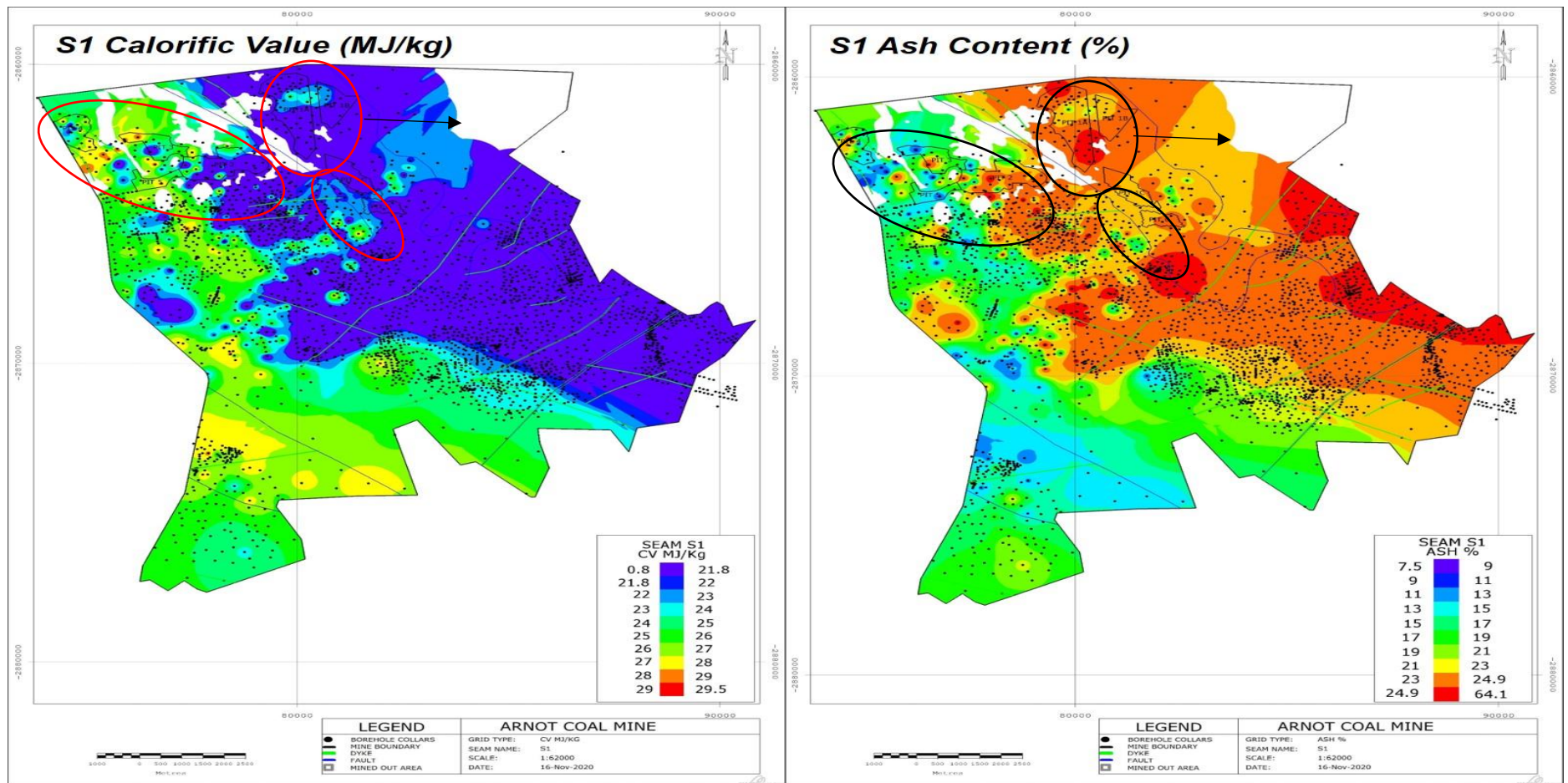


Figure 25. Calorific value and ash plots for S1 (Arnot Opco, 2020).

5.8 Coal Product

The mine produced coal for Arnot Eskom. The power station expected coal with specific quality parameters listed in Table VI below.**Error! Reference source not found.**

Table VI: Arnot Power Station coal specification (Arnot OpCo, 2020).

Parameter	Rejection limit
Calorific value (CV)	< 21.80 MJ/kg (as received)
Ash	> 31.0%
Total sulphur (TS)	> 1.0%
Volatile matter (VM)	< 21.0%
Abrasive index (AI)	> 464.0 mgFe/4 kg

5.8.1 Calorific Value trends of the product

Coal quality data from 2012 to 2015 were analysed. Subsequent, representative data were unavailable before March 2012. The data indicate underground ROM qualities as opencast mining concluded in 2011.

Figure 26 indicates a highly variable ROM CV attributable to the orebody's variable in situ physical and chemical properties, including contamination. Eskom required a CV of $\geq 23.3\text{MJ/kg}$ (air-dried basis); the mine predominantly did not meet the CV requirements for the years analysed.

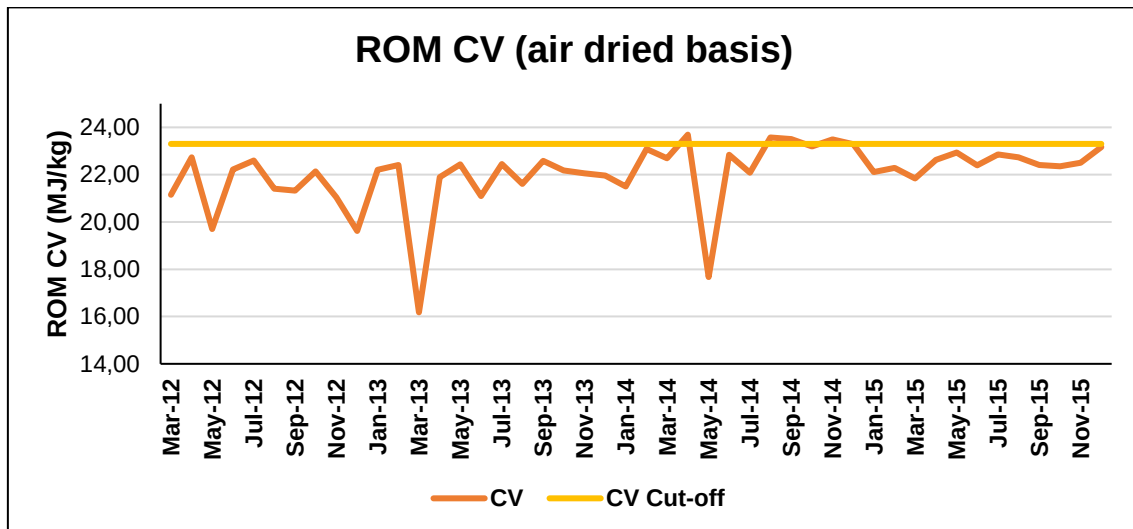


Figure 26. Historical calorific value trend (Data Source: Arnot OpCo Database).

5.8.2 Abrasive Index product trends

The significance of AI in coal is that the higher it is, the higher the wear rate on the boiler tubes at Eskom's power stations, resulting in higher maintenance costs and downtimes. Figure 27 indicates that AI did not meet the Eskom quality specification except for three months in the years studied. This was owing to the ore morphology (in-seam parting and floating stone), contamination, and the mining standards. The AI of the coal delivered to Eskom was predominantly above the rejection limit of 464 mgFe/4 kg .

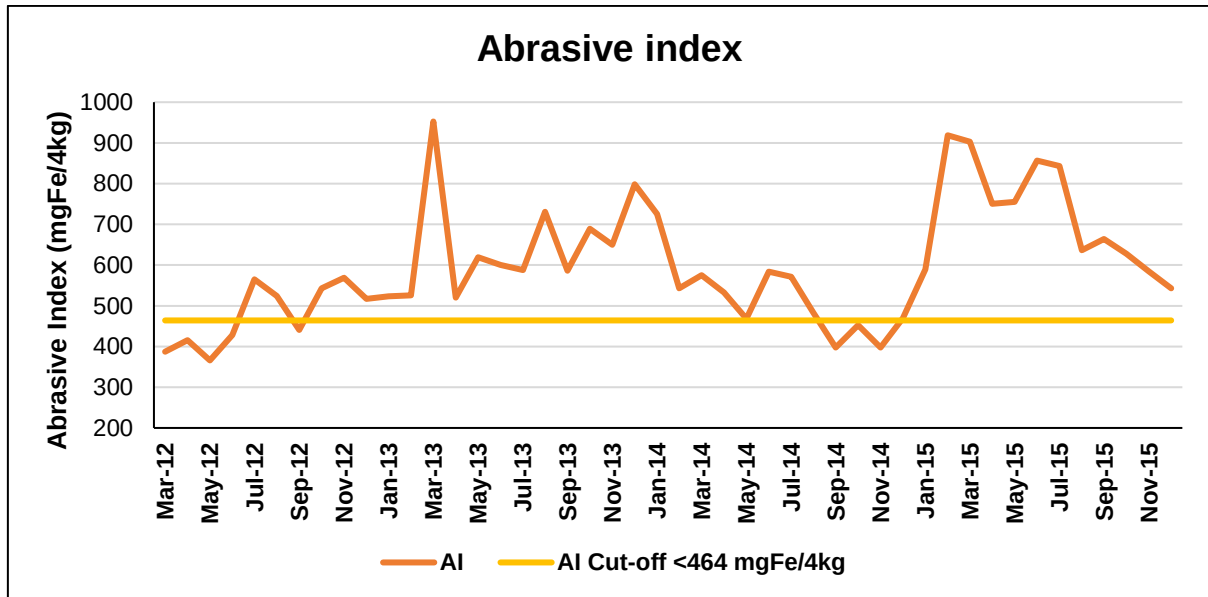


Figure 27. Historical abrasive index trend for ROM coal (Data Source: Arnot OpCo Database).

5.9 Production Costs

Over the years, the working cost increased exponentially (Figure 28). The cost data were sourced from annual financial reports. Between 2010 and 2015, the costs increased by 70%. This increase could be attributed to several management factors. An obvious factor was the production decrease and instability over the years.

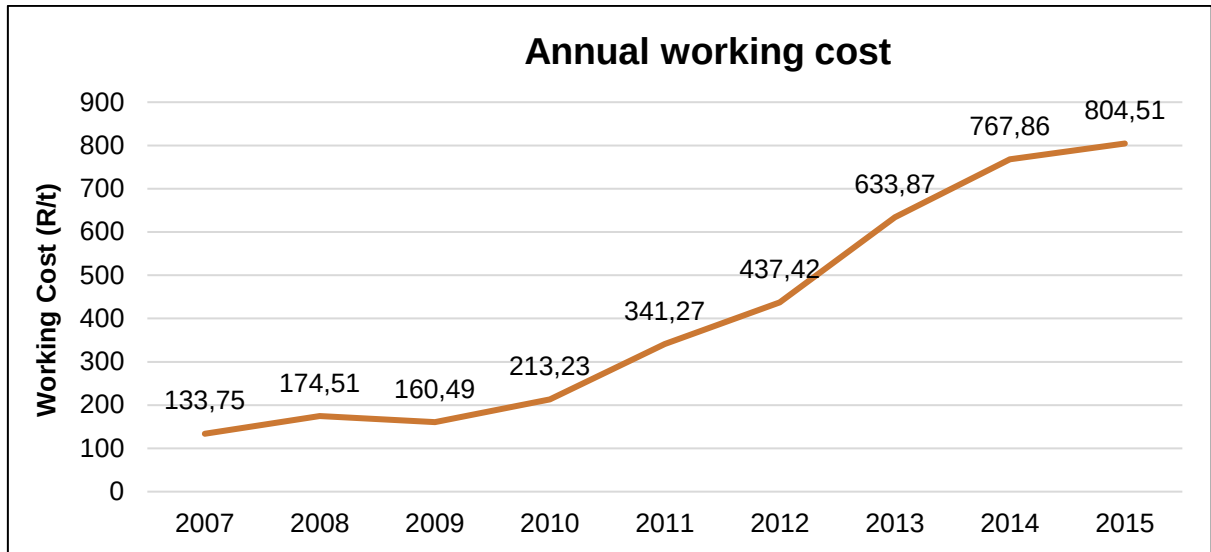


Figure 28. Annual working costs from 2007 until mine closure (Data source: Arnot Opco database).

5.10 Conclusion

Throughput and quality trends reveal high system variability, emphasising the system's instability. Production cost increased with decreasing production tonnes. Contamination was higher than planned, therefore, directly influencing quality parameters, such as AI, CV, and ash. The subsequent chapter presents the causal loop diagrams and scenario planning. It aims to demonstrate the flow from geology to mining and the plant.

6 SYSTEMS THINKING APPROACH FOR VALUE CREATION

6.1 Introduction

This chapter extends the previous chapter, presenting the scenario model and causal feedback loops of the system. The objective is to demonstrate value creation across the value chain by considering the chemical properties, physical, geological, and mining conditions. This is based on Eskom being the market, excluding export coal. The scenarios demonstrate contamination influence throughout the system and how it affects the yield. The coal's chemical properties are attributable to their interdependencies and influence on the plant processes throughout the system. Material flow throughout the system through mine and plant processes is considered. Full integration of the KPIs across the CPA in the value chain is assumed for Scenarios 1 and 2 (refer to Chapter 3).

The coal seams' physical and chemical properties are heterogeneous across the mine. The roof and floor at ACM are sandstone and siltstone, while the in-seam parting ranges from siltstone to shale. Section 1 to 4 from two shafts (10 and 11) hold different seam thicknesses, chemical properties, and physical conditions (Figure 29). The RD of the coal across the two shafts is slightly different owing to the in situ chemical properties of the coal, but within the range between 1.36 to 1.55 g/cm³.

The base case is based on actual historic conditions; the data were generated from grade control reports for both shafts. Scenarios 1 and 2 are modelled cases,

reflecting mining practices and integration influence on production, plant efficiency, and product qualities.

6.2 Mining

Figure 29 presents a graphical illustration of the three scenarios modelled. The advance per metre was calculated for four sections in each scenario. All four sections held the same seam height and in-seam parting. The base case was the historical case where the contamination was inadequately managed as it was higher than planned.

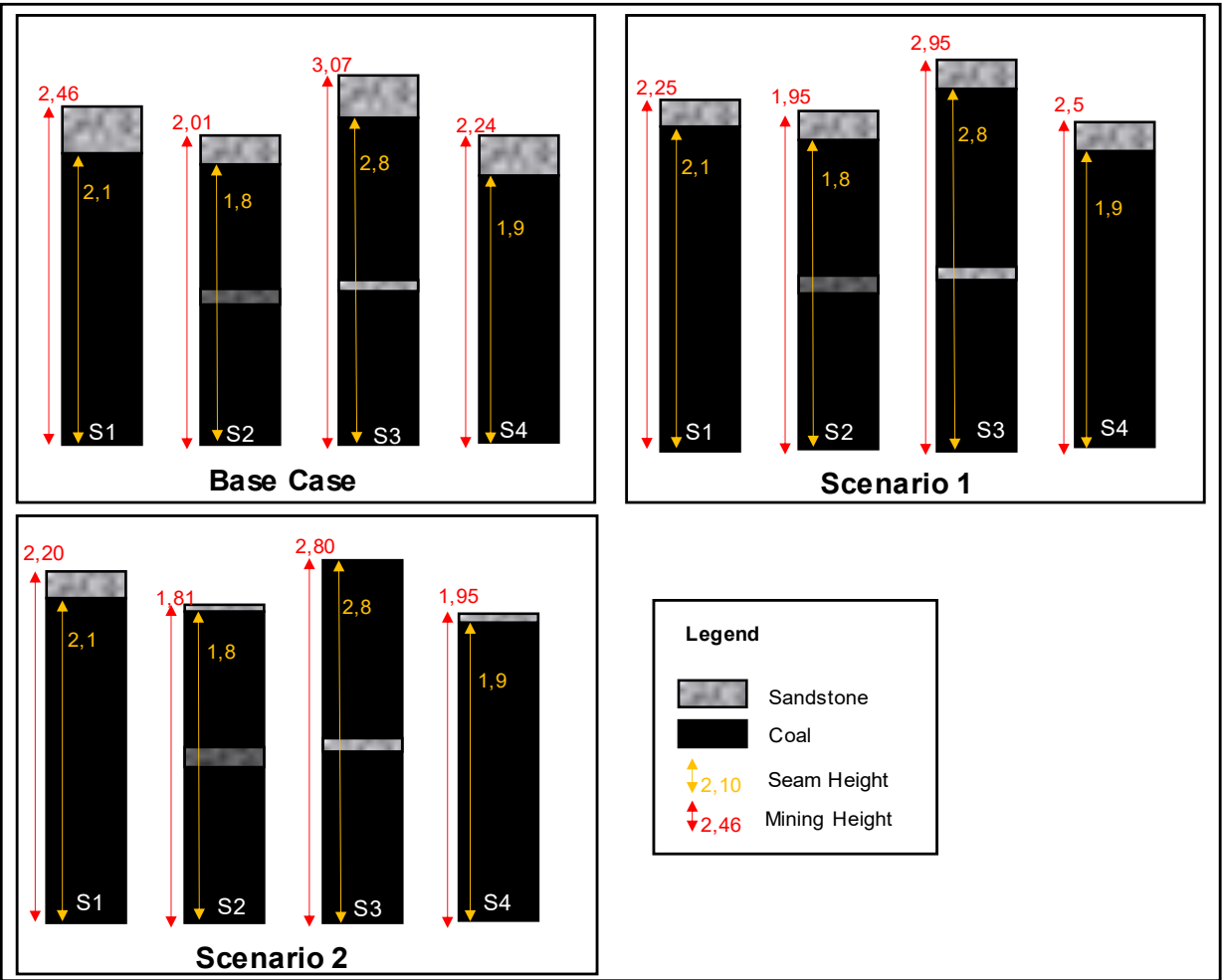


Figure 29. Modelled scenarios for four sections.

Error! Reference source not found. summarises the throughput model (APPENDIX A). Scenario 2 considers the maximum allowable out-of-seam contamination from the roof and floor cut off 15cm for all sections. The total tonnes produced per metre advance decreases by 7.6% (from 116.85 t to 104,15 t) mainly due to the reduction in overcutting the roof and floor. Contamination decreases by 37.9% by adhering to the maximum allowable out-of-seam contamination for the sections. By reducing the contamination, the plant efficiency increases from 83% to 95% as the ROM feed to the plant improves; therefore, the yield increases by 10.7% (from 75,47% to 86,19%). The working cost (R/t) is reduced by 8.23% when considering the physical properties of each section, the mining rate, and plant efficiency improvements.

Table VII: A summary of the throughput improvement model.

	Base case	Scenario 1	Scenario 2
Tonnes/Metre Advance	116,85	109,17	104,15
Total Contamination (t)	20,27	12,59	7,57
Plant Efficiency	83,00%	95,00%	97,00%
Product Yield	75,47%	86,19%	88,72%
Product Tonnes	73,34	83,74	86,16
R/t Cost	R 387,31	R 357,34	R 351,41

Scenario 3 represents an optimised case where mining is performed under stringent standards for grade control to manage out-of-seam contamination where possible, with a great understanding of the geological conditions of each section. The plant ROM tonnes and working costs were reduced by 13.0% and 9.3%, respectively. Plant efficiency and product yield improved further.

The cost calculation assumes a 60% fixed cost and 40% variable costs split. The tonnes per metre advance decreases in each scenario; however, the yield increases, and the working cost decreases. In each scenario, the total contamination decreases; therefore, the yield increases owing to less non-coal material incorporated into the ROM. The cost is inverse to volume due to economies of scale; therefore, working cost decreases as the product tonnes improve.

6.3 ROM Feed Qualities

Undulating roof and floor, in-seam parting, and structural complexities characterise the mine. The roof and floor are sandstone and shale, whereas the in-seam parting is mainly shale.

The raw in situ are assay qualities adopted from the geological model based on exploration and grade control borehole samples. The contamination composition affects the ROM quality. Due to the contamination lithology being sandstone, ash increases, and the CV and volatile content decrease. The parameters are within the Eskom specification (**Error! Reference source not found.**), by reducing the contamination by 10.88%. APPENDIX C displays the key inputs and calculations.

Table VIII: The influence of contamination on ROM qualities.

	Tons (Mtpa)	Seam Height (m)	Mining Height (m)	Total Contamination (m)	Contamination (%)
Section 1	72000	2,10	2,46	0,36	20,67
Section 2	72000	1,80	2,31	0,51	30,10
Section 3	72000	2,80	3,20	0,40	17,84
Section 4	72000	3,74	4,08	0,34	12,14
Total	288000	2,61	3,01	0,40	20,19
<i>Eskom Specification</i>					

Raw In-Situ Qualities			
Ash (%)	CV (MJ/kg)	Vols (%)	TS (%)
23,60	21,15	22,85	0,78
16,17	25,59	24,37	0,93
18,65	24,97	29,85	0,51
23,60	22,15	22,85	0,78
20,51	23,47	24,98	0,75

ROM Qualities (Inc Contamination)			
Ash (%)	CV (MJ/kg)	Vols (%)	TS (%)
32,17	18,24	20,96	0,68
30,74	20,22	21,18	0,74
26,50	22,01	27,49	0,45
28,42	20,76	21,86	0,72
29,46	20,31	22,88	0,65
24,90	21,80	22,10	0,96

	Tons (Mtpa)	Seam Height (m)	Mining Height (m)	Total Contamination (m)	Contamination (%)
Section 1	72000	2,10	2,25	0,15	9,79
Section 2	72000	1,80	2,25	0,45	27,54
Section 3	72000	2,80	3,08	0,28	13,19
Section 4	72000	3,74	3,89	0,15	5,75
Total	**288000**	**2,61**	**2,87**	**0,26**	**14,07**
Eskom Specification					

Raw In-Situ Qualities			
Ash (%)	CV (MJ/kg)	Vols (%)	TS (%)
23,60	21,15	22,85	0,78
16,17	25,59	24,37	0,93
18,65	24,97	29,85	0,51
23,60	22,15	22,85	0,78
20,51	23,47	24,98	0,75

ROM Qualities (Inc Contamination)			
Ash (%)	CV (MJ/kg)	Vols (%)	TS (%)
27,51	19,82	21,99	0,73
27,82	21,30	21,82	0,78
26,12	22,18	27,51	0,46
27,51	20,76	21,99	0,73
27,24	21,01	23,33	0,68
24,90	21,80	22,10	0,96

	Tons (Mtpa)	Seam Height (m)	Mining Height (m)	Total Contamination (m)	Contamination (%)
Section 1	72000	2,10	2,20	0,10	6,75
Section 2	72000	1,80	2,11	0,31	20,75
Section 3	72000	2,80	2,93	0,13	6,59
Section 4	72000	3,74	3,82	0,08	3,15
Total	**288000**	**2,61**	**2,77**	**0,16**	**9,31**
Eskom Specification					

Raw In-Situ Qualities			
Ash (%)	CV (MJ/kg)	Vols (%)	TS (%)
23,60	21,15	22,85	0,78
16,17	25,59	24,37	0,93
18,65	24,97	29,85	0,51
23,60	22,15	22,85	0,78
20,51	23,47	24,98	0,75

ROM Qualities (Inc Contamination)			
Ash (%)	CV (MJ/kg)	Vols (%)	TS (%)
26,26	20,25	22,26	0,75
24,66	22,46	22,51	0,82
22,35	23,59	28,69	0,48
25,75	21,38	22,38	0,75
24,76	21,92	23,96	0,70
24,90	21,80	22,10	0,96

6.4 The Plant

The plant process flow includes a crush and screen module and a dense medium separation (DMS) or the sink-and-float process. The DMS plant is the beneficiation module where the coal is beneficiated to improve qualities to meet the market's specification. According to Groppo (2017), the DMS is more efficient with 7%-10% near-gravity material, however with a near-gravity material of >10% the processes must be tightly controlled. The DMS efficiency decreases with 25% near-gravity material, and it is applied in limited situations (Groppo, 2017). The washing plant efficiency also depends on the feed composition, feed particle size, feed rate in the unit, and plant maintenance (Bhattacharya, et al., 2015).

Table IX demonstrates ROM and product qualities after washing, operating at 97% plant efficiency and beneficiating at the correct RD based on the plant feed. Raw qualities do not meet the client's specifications on ash (Scenarios 1 and 2). All parameters will improve when the coal is beneficiated to an ash content of below 24.9% owing to the relationship of the chemical properties of the coal.

When 60% of the coal is crushed and screened, the remaining 40% is washed. The total yield of 94.84% is calculated using a weighted average after blending 40% beneficiated coal and 60% raw ROM coal (Table IX).

Table IX: Total product yield after washing 40% and crushing and screening 60%.

Total product yield		
Million tonnes per annum		3,43 Mtpa
Crush and screen by-pass (60% Feed)	99,50% Yield	2,06 Mtpa
Full DMS wash (Feed 40%)	87,81% Yield	1,37 Mtpa
Total yield	94,83%	3,25 Mtpa

The plant should beneficiate the coal to qualities meeting the specification after blending, depending on the raw ROM qualities. The cut-off limits for all the quality parameters must be considered. The average ROM qualities are based on actual data from the LOMP for underground reserve areas (Arnot Opco, 2020). The average final product qualities exceed the Eskom specification on all parameters (

Table X).

Table X: Product qualities after 60% unwashed and 40% washed blending.

	Average Arnot ROM qualities	Product qualities after beneficiation	Average final product	Eskom qualities
CV(MJ/kg)	22,86	25.98	24,51	≥21,8
Ash (%)	25,31	16.84	19,87	≤24,9
Volatile matter (%)	23,57	27.11	26,77	≥22,1
Sulphur (%)	0,74	0.54	0,76	≤0,96

6.5 Causal Loop Diagram

A causal loop diagram is a systems dynamics technique to solve complex problems by visualising how parts of a system interrelate and maps feedback.

The causal loop in

Figure 30 is based on and supported by the analysis and data in the previous chapter. The diagram comprises six feedback loops, devising all the dependencies and variables, contributing to the variability of the throughput and product quality.

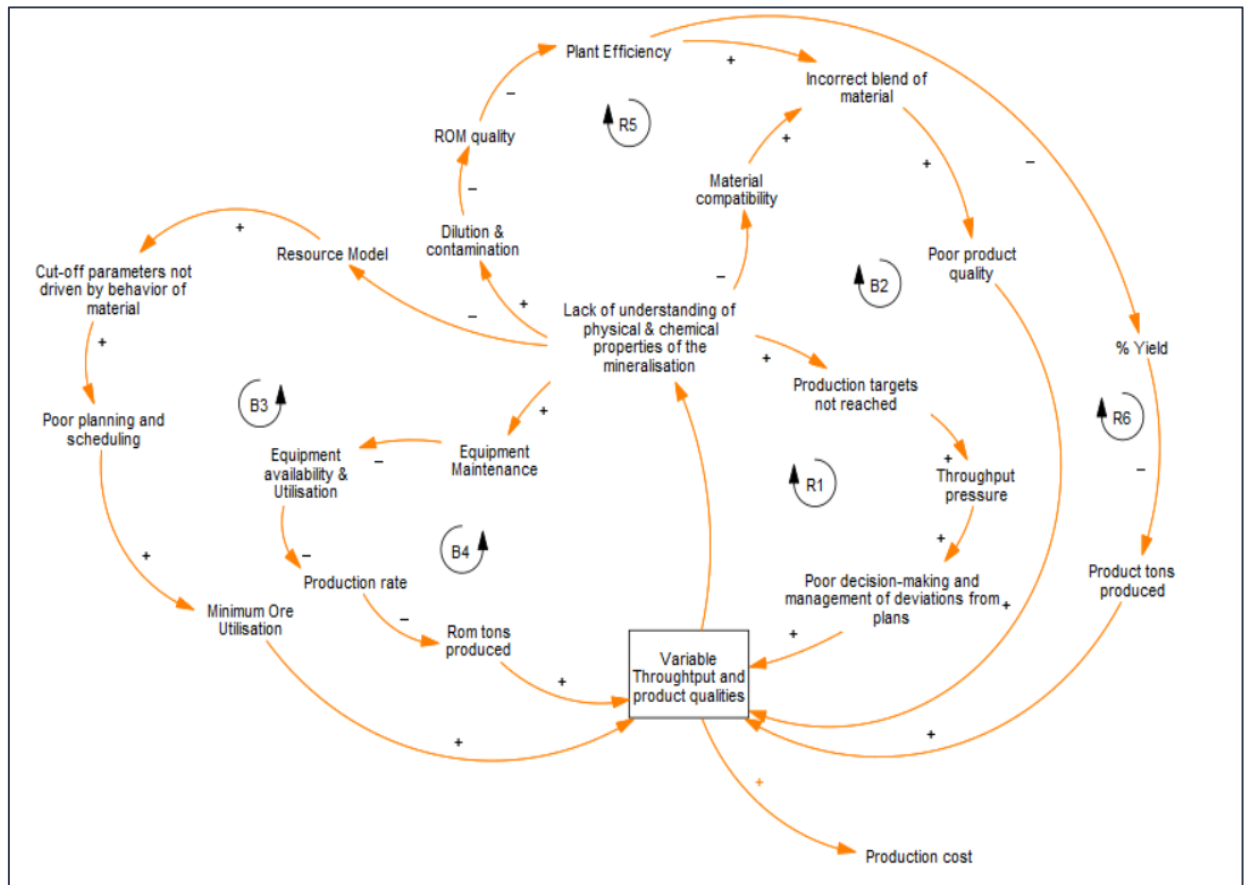


Figure 30. Causal loop diagram for variable throughput and product quality.

The variables have a positive (+) or negative (-) polarity. The six feedback loops are balancing (B) or reinforcing (R). The reinforcing loops compound the change in one direction and can cause growth or collapse; therefore, a distinct behaviour

will continue if unchanged. The balancing loop is goal-pursuing and always pursuing equilibrium. The feedback loop is denoted by either R or B.

6.5.1 Loop 1 (R1)

Insufficient understanding of the orebody's physical and chemical properties increases the likelihood of not reaching production targets owing to geological challenges not accounted for in plans. This causes increased throughput pressure. The decision-making process is not synchronised to manage the deviations from the plans lacks integration; therefore, this reinforces the system's instability.

6.5.2 Loop 2 (B2)

The orebody knowledge supports the understanding of raw material compatibility. If the latter is poorly understood, incompatible material being blended results in product quality failing to meet the required market specification.

6.5.3 Loop 3 (B3)

The resource model depends on the orebody's data based on its orientation, chemical composition, and structural complexities. This enables applying optimum cut-off parameters based on the Reasonable Prospect for Eventual Economic Extraction (RPEEE), as prescribed by the South African Mineral Resource Committee (SAMREC) Code. If cut-off parameters are substandard, the extraction strategy of the mine will not align with the system's primary goal.

The medium to short-term planning and production schedule will, therefore, oppose maximum ore extraction and use.

6.5.4 Loop 4 (B4)

The chemical composition of the coal, roof, and floor dictates the hardness of the material. Structural geological complexities, such as faults and physical properties of the orebody, including undulating roof and floor, affect how the CM must cut coal based on the conditions underground. Cutting more sandstone wears off the peaks of the CM faster, therefore, leading to increased frequency of CM maintenance. This affects the availability and use of equipment, therefore, increasing standing time and reducing the production rate. The decreased production rate leads to unmet targets and decreases mined ROM tonnes.

6.5.5 Loop 5 (R5)

The contaminant composition (sandstone and shale) affects ROM qualities and plant processes. A lack of orebodies knowledge disturbs material flow in the system. Increased contamination contains a higher percentage of near-gravity material; therefore, it reduces the plant efficiency. This will result in material blending challenges and a product that does not fulfil the required specification.

6.5.6 Loop 6 (R6)

Contamination affects ROM qualities. Increased contamination contains a higher percentage of near-gravity material. This affects the plant efficiency as the plant

beneficiates using a medium with an established RD for the float and sink process, depending on the specification of the required product. A plant not running at its optimal performance decreases the potential yield of the system leading to more coal lost in the discard.

6.6 Conclusion

This chapter demonstrates the base case, and the optimised scenario indicating significant improvement in the yield, cost, qualities, and plant processes. A feedback causal loop demonstrates interdependent variables and network of links relating to the research problem. Constructing from this chapter, the subsequent chapter discusses the results and findings of Chapters 5 and 6.

7 DISCUSSION

7.1 Introduction

This chapter deliberates the previous chapters' findings. The system archetypes resulting from the feedback loop analysis as well as causes and effects of the unstable system demonstrated in Chapter 5 are discussed. The lack of end-to-end integration of processes along the value chain eroded value. Variability within the system is clear from the data analysed. The efficiency and system performance were inevitably affected. The compounding influence of interdependencies of multiple variables affected the business performance as the working cost increased to R804.51/t.

The prerequisites of flow-based, synchronised geology, mining, and plant systems are considered. The importance of ROM alignment with the market requirements from a volume and quality perspective is emphasised while recognising a mining operation as a socio-technical system.

7.2 Socio-Technical System

The historical data signifies that the ROM quality and quantity, mining processes, and beneficiation processes are misaligned with the market's quality and quantity specifications. This signifies the inefficiencies of the processes, lack of flow within the systems, and variability influencing the entire system's behaviour.

According to Ropohl (1999) thinking is nurtured by knowledge and practice. In present days, the knowledge is informed by science and most human practices

are largely affected by technology (Ropohl, 1999). A socio-technical system emphasises the reciprocal interrelationship between humans and machines with the purpose of shaping the technical and social conditions so that efficiency and humanity can co-exist (Ropohl, 1999). According to Husserl (2011), the context of comprehensive understanding has been neglected by specialised science therefor the inability to synthesize heterogenous knowledge regarding problems emerges. The transformation of a system with regards to input, state and output can be considered as matter, energy and information. A socio-technical system requires a hierarchy of action systems (Ropohl, 1999), action in this context includes work and communication between functional departments (geology, mining and the plant).

Mining is a socio-technical system that transforms matter, information and energy as the main agents of physical work. Moreover, physical work requires the coordination of information and communication. A goal setting system provides the guidelines for communication and work (Ropohl, 1999). According to Jambekar (2000), systemic structures emerge owing to managerial responses to challenges of meeting production deadlines and throughput pressures. There are significant feedback loops that emerge from the information and work subsystems.

The total contamination was significantly high because of throughput pressures emerging from failure to meet production targets and the misalignment of KPIs across the value chain. For example, one of the performance measures for the mining department was ROM tonnes produced (not classified into waste and

coal). This resulted in overcutting the roof and floor to increase the ROM tonnes produced without understanding the influence of the contamination downstream. This demonstrates the lack of understanding and knowledge of the interdependencies of production variables and their influence areas across the value chain. The contamination had a ripple effect on the system and the impact was evident on the yield, plant processes, product qualities and the overall cost.

According to Donovan et al. (2017), multiple human and non-human factors enable decision-making. People in any organisation need to understand their function in the business's strategy, its targets, and day-to-day operations. Employees need to grasp how their functions, link to the organisation's purpose and how they affect the entire system's performance. Each system and subsystem component (human and non-human) directly affects parts of the system, although sometimes not obvious.

The examination of the network of links between each influencing factor, decision, and action shapes the system's performance during deviations. The value chain visibility permits employees to understand how their actions influence the dynamics of the entire system (Jambekar, 2000). Deviations from the base plan within any operational environment, either negative or positive, will exist. Vertical and horizontal synergies across all the levels of work in the system can help build a resilient system efficiently by handling positive and negative deviations. The favourable variations must be evaluated from the feedback loops in the system and exploited, whereas the negative deviations must be evaluated to determine the best-case scenario.

Process alignment and critical performance variables can improve business performance by increasing product sales and reducing production costs. This ensures that CPAs and KPIs are integrated across the value chain. MRTM combines variability in physical operating conditions, characteristics of the plant processes, and the ore's attributes into the decision-making process and business logic.

7.3 Cause and Effect from Causal Loop Diagram

Feedback loop diagrams illustrate system archetypes; therefore, understanding the feedback enables managers to cope with complexity and improved decision-making aligning with the system's goals (Jackson, 2003). Systems dynamics can become a unifying, interdisciplinary framework, infiltrating beyond the surface details presented by individual departments. This could enable a deeper understanding of the patterns generating the behaviour (Jackson, 2003).

The causal loop diagram (4) captured the causes and effects of the ACM variable throughput and product qualities before closure. According to the systems thinking principle, an issue or its constituents cannot be understood in isolation. The variables' relationship will, therefore, instigate the system's outcome and behaviour. The collective influence of the variables shapes the system. Understanding the variables enables employees to manage and make informed decisions aligned with the system's goal.

Figure 31 illustrates the causes of the main issue and the connectivity of the links in this system. The full potential and capacity of the orebody are reduced owing

to inadequate planning. The increased maintenance frequency, influencing the utilization and availability of equipment, affects the production rate. The latter directly affects the coal volumes produced and the system's ability to meet production targets.

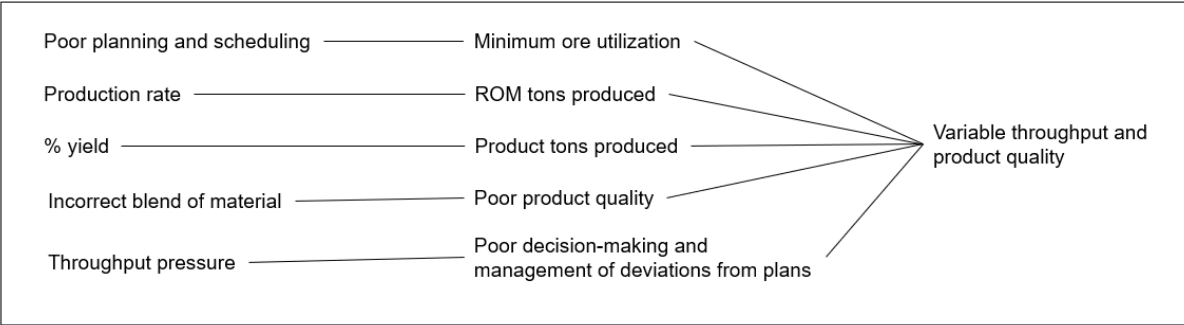


Figure 31. Cause tree for variable throughput and product quality.

The ROM feed quality and tonnes produced directly affect the plant and the efficiency of the processes. The system's yield is directly affected by the quality and quantity of the coal produced. The latter is also affected by incorrect blends of material and the knowledge of how the material behaves in the system.

The lack of knowledge of the ore body and the mineralisation characteristic has multiple influences on the system (Figure 32). This contributes to the resource model's accuracy and how the information will be filtered to other participants in the value chain, relying on the information for maximum extraction of coal and decision-making. The nature of the ore body affects the in-situ coal quality and the material diluting and contaminating the coal. The coal and the contamination

material behave differently during the beneficiation process owing to diverse chemical compositions.

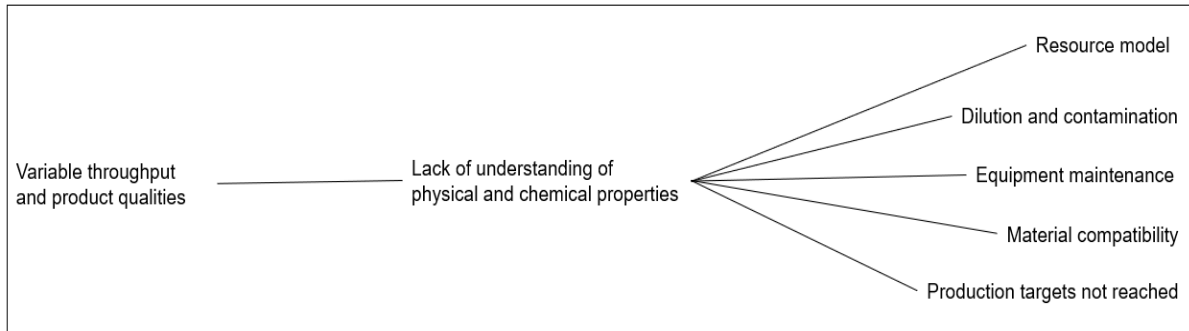


Figure 32. Effect tree (from the feedback loops) for variable throughput and product qualities.

The CM machine's primary purpose is to cut coal. Coal and sandstone or shale have varying hardness owing to their chemical composition; therefore, cutting more sandstone slows down the cutting rate of the CM, wearing off the peaks on the cutting drum quicker. This leads to more stoppages to change peaks. An increased maintenance frequency of the machines, causing decreased machine availability and utilization.

Variable throughput and product qualities result from interconnected constituents in the system. The causes and effect diagrams are solely based on analysing the research data. The variables from an organisational level, contributing to the non-performance of the system, may be extensive, proving the complexity of the mining environment. All the variables, directly and indirectly, affect the cost at each functional stage within the value chain. Unmanaged variability at the

operational level may lead to emergent properties at an organisational level, affecting the business' performance and market position.

7.4 System Archetypes

Causal loop diagrams are significant to indicate system behaviour. The behaviour of the holistic system is clear from the feedback loops discussed in Chapter 6. System archetypes help to recognise common behaviour patterns. The dynamic variables' interrelations are more explicit. System archetypes are considerable because slight changes in the initial conditions can significantly change the system's long-term behaviour. Kim (2008) provides guidelines for identifying the system archetypes and three system archetypes were identified from the causal loop diagram.

7.4.1 Drifting performance

Drifting performance is a system behaviour leading to worse conditions by continuously lowering the expectation (Kim, 2008). This system behaviour is demonstrated in loops R1 and B3. With ACM, the production goal was reduced owing to increasing throughput pressure and management's decision-making; therefore, increasing the costs as the human resource, equipment, and asset maintenance cost, did not reduce with the scaled-down production.

A reserve model used for short, medium, and long-term planning, requires input data from the resource model. The resource model is fed by data generated by preceding processes, such as exploration, sampling, quality assurance, and

database management. The model's precision and accuracy are based on competence and the input data quality. An inaccurate resource model, therefore, leads to a suboptimal reserve model, continuously reducing the ore's full exploitation potential and use. If competence worsens over time, it will affect the quality of the input data therefore disintegrating the flow of information.

7.4.2 Fixes that fail

This archetype results from focusing on short-term fixes and not the fundamental problem. A symptomatic problem is recognised, and a solution is quickly implemented to ease the symptom, therefore, not fixing the real problem (Kim, 2008). This causes a short-lived resolution and unintended consequence.

To combat production pressures and non-performance—a zama zama shift system was introduced where the mining team could work overtime on weekends to combat monthly production shortfalls. Volumes were prioritised over quality due to the bonuses aligned with production. This gave rise to loops B4, R5 and R6. Introducing the zama zama shift solved a problem symptom of not meeting production targets. However, each machine was cutting more contamination even when the seam conditions were above their minimum cutting height. (as illustrated in Chapter 5, Figure 20, Figure 21, and Figure 22).

The unintended consequence resulting from zama zama was contaminated coal affecting the feed and product qualities. Contamination affects the near-gravity

material in the plant feed, therefore, influencing the separation rate and medium's effectiveness.

7.4.3 Shifting the burden

This archetype is characterised by a problem symptom prompting intervention and the implemented solution solves the problem swiftly. The symptomatic solution diverts attention from the real problem and subtly causes the deterioration of the real solution over time (Kim, 2008). The behaviour was identified in two scenarios from the causal loop diagrams (Table XI).

Table XI. Shifting the burden system archetypes identified from CLD.

Problem symptom	Symptomatic solution	Fundamental solution	Side effects
Compliance with plans.	Reducing production targets and trends.	Condition-based planning, material flow, and CCR.	Increased working cost.
Increasing cost (R/t).	Implementing zama zama to combat non-performance and meet production targets.	Process & KPI alignment (Geology, mining & plant).	Reliance on zama zama bonus for performance resulting in slow production rate during the week.

The variance in the budgeted tonnes and actual tonnes (Chapter 5, Figure 16) is owing to non-compliance with plans and failure to meet production targets. The symptomatic solution was to reduce the budgeted tonnes (from 3.4 Mtpa in 2010 to 1.7 Mtpa in 2015) over time to meet the target. The side effect of such management decision led to an exponential increase in working costs over time.

Increased working costs prompted an intervention to increase production through zama zama to counteract the cost. Improved production would cause increased throughput; however, the symptomatic solution led to a high reliance on the zama zama remuneration bonuses by the mining department without optimised performance. Production would be slow during the week to compensate for the shortfall on weekends and to receive a bonus. An implicit operational culture that is not performance driven developed as an emergent consequence of the behaviour.

The fundamental solution to the real problems is to ensure integration and alignment of KPIs for functional departments by implementing change management at all levels (from operator to manager). This would assist to repair and integrate the social and technical subsystem.

7.5 Flow Within the System

A flow-based system has prerequisites that must be considered to ensure that it functions to its maximum potential (Laurens, et al., 2020). The understanding and knowledge of material flow and the fundamental changes the material experiences through the production process are some prerequisites. This

requires resource and processing characteristics of the system knowledge to maximise ore use, production, performance management, and process efficiency.

The model (APPENDIX A) is simple, illustrating the material flow from areas with various conditions throughout the processes. Value can be lost through inadequate exploitation of the capacity within the system. For an optimised system, CCR, such as the following, must be considered:

- Resource model;
- Mine design;
- Plant capacity and efficiency;
- Equipment availability and utilization;
- Pit design (for opencast);
- Buffers (stockpiles and silos); and
- Material flow and changes through the system.

The functional observation of the value chain must erode to enable a flow-based system with clear interdependencies of all variables captured for vertical and horizontal integration and decision-making across all levels. This is enabled by understanding the factors, as discussed below.

7.5.1 Orebody morphology

Orebody morphology includes the orebody's physical nature. In ACM, this includes structural complexities, floor and roof undulations, floating stones, seam thickness changes, and in-seam partings. Changes in the ore body morphology influence the ROM and the product capacity (as stated in the model with differential seam thicknesses and total contamination from each section). The knowledge of the morphology of the ore develops an understanding of how the ROM quality, production rate, process efficiency, beneficiation potential, and cost will be influenced by variations in the plan.

7.5.2 Chemical properties of ore

The chemical properties of ore refer to the characteristics of coal mineralisation and the relationship among the parameters. Variations in the chemical characteristics influence the ROM quality, product quality, yield, beneficiation efficiencies, and contaminants affecting the plant processes.

7.5.3 Changes in the material's characteristics through the system

Addition of material, such as contamination or loss of material from crushing, fines, and fragmentation may change the quality of the coal as the quantity changes throughout the production process. This may have some cost implications owing to material rehandling and low yield.

7.5.4 Material compatibility in the system

The coal composition will differ from other reserve areas owing to the varied ore body morphology and chemical characteristics. Coal's reaction throughout the process will vary until the final product quality and quantity for each combination of ROM scenarios are reached. The flow and how the coal behaves will influence the production cost.

7.6 ROM Alignment with the Market Product

From the model (Figure 33 and APPENDIX A), the throughput constraints affecting how the system behaves relating to the creation or erosion of value were identified, based on their influence on the working costs:

- Physical conditions (seam height, dip, and geological complexities);

- Chemical characteristics (RD and in situ quality);
- Contamination mined;
- ROM tonnes; and
- Plant efficiency.

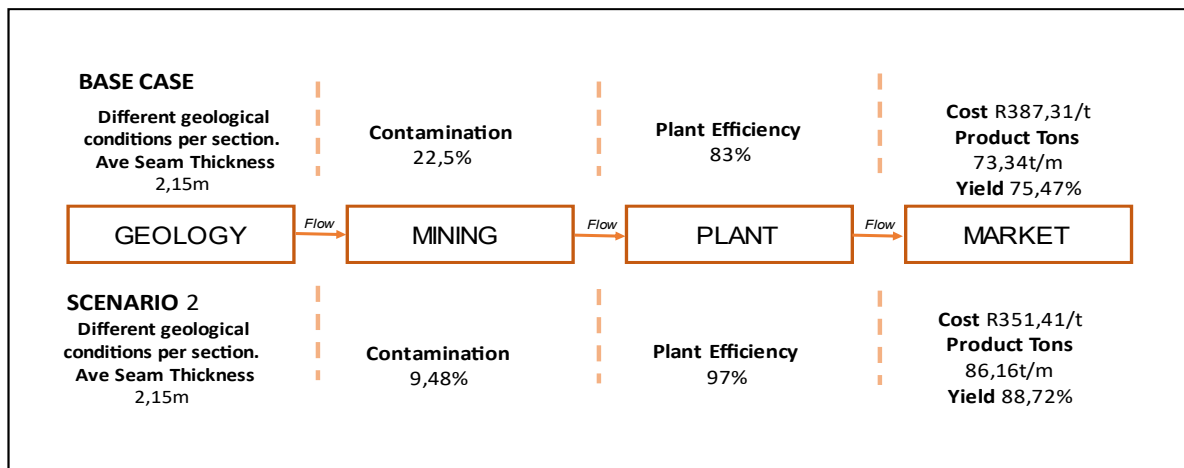


Figure 33. Process alignment from geology to market.

The variability inherent in the geology dictates the throughput and the effectiveness of the processes downstream (Claassen & Laurens, 2016). The alignment of ROM and product quality, considering the contamination within the system, illustrates how only key drivers can affect the total process efficiency, product yield, production, and production cost.

The ultimate income-generating product is not only determined by the ROM quantity and quality; it is a non-linear process requiring recognising the system structure, variables, and the flow (material, information, and synergy) within the entire system.

The planning process scheduling production should incorporate the physical conditions (orebody morphology), chemical characters of the mineralisation, and the LOM considering maximum ore use. Planning aligning ROM with the product enables the understanding of material combinations and how it material will flow throughout the system to achieve maximum product and process efficiency. The plant processes must be designed and managed considering the physical conditions. This relies on the knowledge of the system structure, understanding the feedback loops and the recognition of the interconnections. Various variables influence the throughput and system performance differently; therefore they must align with physical conditions, downstream processes, and market requirements.

7.7 Condition-Driven Standards

Variability is incorporated by developing condition-driven standards directly connected to geological and processing conditions, according to the MRTM approach (Claassen & Laurens, 2016) and (Laurens, et al., 2020). This incorporates classifying the ore body into the three dimensions (physical material flow, product payability, and logical decision-making). Orebody classification considers in situ chemical and physical parameters, material behaviour through the system, material influence on process efficiency, and the influence of mining conditions.

The orebody classifications allow for condition-driven planning and scheduling based on the ground conditions. For example, in areas where the seam height is consistently above the cut-off and the roof is competent, there should be no

contamination planned for that panel. This will allow for improved ROM qualities and better yield.

7.8 Conclusion

The chemical properties of the material and the morphology of the coal seam significantly influence the mining and the economic value of the coal. How the seam is defined, material variability, mining rates and standards, equipment type, plant's beneficiation potential, and processes influence the entire system's product, performance, and throughput. Knowledge of these variables must be present throughout the planning process. The subsequent chapter concludes with the research findings and observations. The interrogation of feedback from the social and technical subsystem enables deeper understanding of challenges and effective integrated management.

8 CONCLUSION

8.1 Introduction

The main objective of this chapter is to summarise and conclude the research findings. The research limitations and contributions are also discussed.

8.2 Research Findings

A socio-technical system requires the interaction of human and non-human factors therefore, the interaction of humans, their motivation and actions shape the system. Managers oblivious to the interdependencies to which their actions contribute are prone to intensify the problems. It is prudent that KPIs are aligned, and employees understand their functions in the operation and how they link to other functions to build a resilient system. Sustainable value creation depends on key value driver management and understanding the system architecture and behaviours.

The physical and chemical characteristics of the orebody have a compounding influence on the system's behaviour, if insufficiently managed. The results suggest processes' inefficiencies and misalignment, a lack of flow within the system, and high variability affecting the entire system's behaviour and stability. The operation did not perform to its maximum potential to realise maximum value from the mineral asset. The relationship among the variables and how they collectively affect the system's performance verifies a non-linear behaviour of a complex system. The instabilities in the system may ripple along the value chain if ineffectively managed, owing to the interdependent nature of activities,

processes, information flow, and resources. The ripple effect is more significant, shifting further away from the source; it may cause a substantial influence on the system. Complete value chain integration can generate an increase in revenue of 20% to 30% (APPENDIX A) by optimising throughput and operating costs.

Thirty-five per cent of the mines apply in-house fit-for-purpose improvement and management methods. A hybrid of methodologies is employed for business process improvements; therefore, systems thinking and MRTM offer immense potential for value creation. This can enable ACM, a junior miner, to be competitive in the market.

Complex systems do not adapt to their environment, but they evolve in response to one another. A STA can create financial value by increasing revenue (through quantities and throughput) and reducing costs for ACM. This can be achieved by ensuring full integration of the value chain, processes, and skills across all the levels in the organisation for better decision-making and maximum ore utilisation. ACM can adopt the approach to manage a complex operational environment to ensure sustainable revenue and survive the cyclic nature of the industry.

8.3 Research Contributions

From the model, the proposed methodology yielded these benefits:

- Reduction in cost;
- Reduced contamination;
- Increase in yield and throughput;
- Improved material flow;
- Improved plant efficiency; and
- Improved ROM qualities.

Hybrid improvement models can produce a positive change in the business depending on the defined goals and the system's architecture. This methodology may optimise ore use and processes, increase and sustain value, lower production cost, and create a stable environment account for variability and dynamism.

8.4 Research Limitations

Limited data were available owing to loss during mine closure. For example, historical plant and mining information was not limited. The mine is not steady enough yet to experiment with the proposed method; therefore, the final phase of the system's thinking framework (implementation and organisational learning) could not be executed. This would have enabled further understanding of

feedback, constraining dependencies, and the system's behaviour towards the environment.

9 RECOMMENDATIONS

The geological model must be re-evaluated for maximum ore use in seam definition. The feasibility of mining low seam areas (<1.8 m) should be considered; as mining equipment low seam environments are available on the market.

The three MRTM dimensions should inform decision making by synchronising the physical material flow, logical decision-making, and product payability. This should enable the operation to execute end-to-end process alignment throughout the value chain. This ensures integrating KPIs, variables, value drivers, and activities across functional departments while dissolving functional boundaries.

The final phase of the systems thinking methodological framework, including implementation and organisational learning, is to be executed. Evaluating feedback loops, emergent properties, and system behaviour should be conducted and filtered down across the organisation. This will enable vertical and horizontal integration to ensure the integration of skills and expertise. Flow-based and condition-driven planning should be implemented to maximise coal extraction. Product sales must be maximised through quality optimisation by aligning ROM with the product.

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APPENDIX A

Table A- I. Geology, mining, and plant integration model.

		Base Case					Scenario 1					Scenario 2				
		Section 1	Section 2	Section 3	Section 4	Total/ Average	Section 1	Section 2	Section 3	Section 4	Total/ Average	Section 1	Section 2	Section 3	Section 4	Total/ Average
Coal	Seam Breadth	6,50	6,50	6,50	6,50		6,50	6,50	6,50	6,50		6,50	6,50	6,50	6,50	
	Seam Height	2,10	1,80	2,80	3,74		2,10	1,80	2,80	3,74		2,10	1,80	2,80	3,74	
	RD	1,48	1,39	1,50	1,35		1,48	1,39	1,50	1,35		1,48	1,39	1,50	1,35	
	tons/m	20,20	16,26	27,30	32,82	96,58	20,20	16,26	27,30	32,82	96,58	20,20	16,26	27,30	32,82	96,58
Total Contamination (Roof/Parting)	Breadth (m)	6,50	6,50	6,50	6,50		6,50	6,50	6,50	6,50		6,50	6,50	6,50	6,50	
	In-seam Parting (m)	0,00	0,30	0,13	0,00		0,00	0,30	0,13	0,00		0,00	0,30	0,13	0,00	
	Roof Cut Height (m)	0,36	0,21	0,27	0,34		0,15	0,15	0,15	0,15		0,10	0,01	0,00	0,08	
	Total Contamination (m)	0,36	0,51	0,40	0,34		0,15	0,45	0,28	0,15		0,10	0,31	0,13	0,08	
	RD	2,20	1,75	1,80	2,10		2,20	1,75	1,80	2,10		2,20	1,75	1,80	2,10	
	tons	5,15	5,80	4,68	4,64	20,27	2,15	5,12	3,28	2,05	12,59	1,43	3,53	1,52	1,09	7,57
ROM tons	Tons/Meter Advance	25,35	22,06	31,98	37,46	116,85	22,35	21,38	30,58	34,87	109,17	21,63	19,79	28,82	33,91	104,15
In-situ ROM	In-Situ Coal Yield	87%	89%	93%	92%		87%	89%	93%	92%		87%	89%	93%	92%	
	Seam tons	17,58	14,47	25,39	30,19		17,58	14,47	25,39	30,19		17,62	14,47	25,39	30,19	
	Roof/Parting Yield	0,01%	0,37%	15,00%	0,01%		0,01%	0,37%	15,00%	0,01%		0,01%	0,37%	15,00%	0,01%	
	Roof/Parting tons	0,001	0,021	0,702	0,000		0,000	0,019	0,491	0,000		0,00	0,01	0,23	0,00	
Product	Plant Efficiency	83%	83%	83%	83%	83%	95%	95%	95%	95%		98%	98%	98%	98%	
	Product tons	14,59	12,03	21,66	25,06	73,34	16,70	13,77	24,59	28,68	83,74	17,26	14,20	25,10	29,59	86,16
	Product Yield	72,21%	73,98%	79,32%	76,36%	75,47%	82,65%	84,66%	90,06%	87,40%	86,19%	85,46%	87,30%	91,96%	90,16%	88,72%
Working Cost	R/t	449,27	513,73	350,30	322,54	387,31	410,97	467,33	325,95	300,24	357,34	402,27	457,62	322,23	295,52	351,41
	R	6 554,13	6 180,81	7 585,95	8 083,08	28 403,97	6 862,02	6 434,42	8 013,85	8 612,04	29 922,33	6 944,78	6 497,05	8 089,54	8 744,27	30 275,64
Revenue	R/t	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00	520,00
	R	R7 585,91	R6 256,27	R11 260,88	R13 031,51	R38 134,57	R8 682,52	R7 159,55	R12 784,92	R14 915,45	R43 542,44	R8 977,26	R7 382,63	R13 054,50	R15 386,42	R44 800,81
Profit (before tax)	R	R1 031,78	R75,47	R3 674,93	R4 948,42	R9 730,60	R1 820,50	R725,13	R4 771,07	R6 303,41	R13 620,11	R2 032,48	R885,58	R4 964,96	R6 642,15	R14 525,17

APPENDIX B

Model Inputs and Calculations

- Tonnes/Metre (t/m) = Seam Breath x Seam Height x RD.
- ROM Tonnes = Coal t/m + Contamination t/m.
- In situ coal yield is based on raw in situ qualities concerning Eskom specification.
- Seam tonnes = in situ coal yield x ROM tonnes.
 - E.g. $20.20 \times 87\% = 17.58$ (Repeat the step for Roof/Parting tonnes calculation).
- Plant Efficiency = Based on plant processes (float and sink medium density) and near density material plant feed material.
- Product tonnes = (Seam tonnes+ Roof/Parting tonnes) x Plant efficiency.
- Plant Yield = Product tonnes/ ROM tonnes x 100.
- Working cost Calculation:
 - The variable cost of total cost = 60%
 - Fixed cost of total cost = 40%
 - Operating cost (R/t) = 365.00
 - Total Cost (TC) = 365.00 x ROM tonnes
 - Variable cost = (TC x 40%)/tonnes
 - $= R\ 146.00 /t$
 - Working cost(R/t) = (variable cost + fixed cost)/tonnes
- Revenue = R/t price x tonnes = R520 x product tonnes
- Profit (before tax) = revenue – working cost

APPENDIX C

Table C- II. Quality data input

SECTION 1	Base Case					
	Thickness	ROM	Ash	CV	Vols	TS
	m	t	%	MJ/kg	%	%
In-Situ Coal	2,10	61 463	23,60	21,15	22,85	0,78
Contamination	0,36	10 537	82,18	1,26	9,94	0,08
ROM	2,46	72 000	32,17	18,24	20,96	0,68
SECTION 2	Thickness	ROM	Ash	CV	Vols	TS
	m	t	%	MJ/kg	%	%
In-Situ Coal	1,80	56 104	16,17	25,59	24,37	0,93
Contamination	0,51	15 896	82,18	1,26	9,94	0,08
ROM	2,31	72 000	30,74	20,22	21,18	0,74
SECTION 3	Thickness	ROM	Ash	CV	Vols	TS
	m	t	%	MJ/kg	%	%
In-Situ Coal	2,8	63 000	18,7	24,97	29,85	0,51
Contamination	0,4	9 000	81,47	1,30	11,00	0,05
ROM	3,2	72 000	26,50	22,01	27,49	0,45
SECTION 4	Thickness	ROM	Ash	CV	Vols	TS
	m	t	%	MJ/kg	%	%
In-Situ Coal	3,74	66 000	23,6	22,15	22,85	0,78
Contamination	0,34	6 000	81,47	1,30	11,00	0,05
ROM	4,08	72 000	28,42	20,41	21,86	0,72

Scenario 1					
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,10	67 200	23,60	21,15	22,85	0,78
0,15	4 800	82,18	1,26	9,94	0,08
2,25	72 000	27,51	19,82	21,99	0,73
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,10	59 294	16,17	25,59	24,37	0,93
0,45	12 706	82,18	1,26	9,94	0,08
2,55	72 000	27,82	21,30	21,82	0,78
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,1	63 529	18,7	24,97	29,85	0,51
0,28	8 471	82,18	1,26	9,94	0,08
2,38	72 000	26,12	22,18	27,51	0,46
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,1	67 200	23,6	22,15	22,85	0,78
0,15	4 800	82,18	1,26	9,94	0,08
2,25	72 000	27,51	20,76	21,99	0,73

Scenario 2					
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,10	68 727	23,60	21,15	22,85	0,78
0,10	3 273	82,18	1,26	9,94	0,08
2,20	72 000	26,26	20,25	22,26	0,75
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,10	62 739	16,17	25,59	24,37	0,93
0,31	9 261	82,18	1,26	9,94	0,08
2,41	72 000	24,66	22,46	22,51	0,82
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,1	67 803	18,7	24,97	29,85	0,51
0,13	4 197	82,18	1,26	9,94	0,08
2,23	72 000	22,35	23,59	28,69	0,48
Thickness	ROM	Ash	CV	Vols	TS
m	t	%	MJ/kg	%	%
2,1	69 358	23,6	22,15	22,85	0,78
0,08	2 642	82,18	1,26	9,94	0,08
2,18	72 000	25,75	21,38	22,38	0,75

- Ash, CV, Vols & TS are actual data from the geological model for both in situ coal and contamination.
- ROM tonnes = (In situ Coal(m) x ROM(m)) / 72 000 = (Contamination(m) x ROM (m)) / 72 000
 - = (1.80m x 2.31m) / 72 000 = (0.51m x 2.31) / 72 000
- ROM qualities (ash, cv, vols & TS) is a weighted average
 - ROM ash = ((61 463 x 23.60) + (10 537 x 82.18)) / 72 000 = 32

